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Increased Energy Efficiency in Manufacturing Systems Using Discrete Event Simulation

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Applied Studies on the Swedish Foundry Industry

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I. Abstract

Market demands are forcing industrial manufacturers to develop their production systems by increasing flexibility, improving quality and lowering production costs. With the help of simulation techniques the understanding of manufacturing systems can be enhanced and alternate solutions can be tested. Simulation has therefore played an important role in industrial development in recent years. New or improved simulation technologies, and new ways to use the available technologies, are still being developed.

Energy related costs are often neglected by Swedish industry due to the low energy costs historically in Sweden, compared to other European countries. The developments of the energy market with uncertainty concerning future prices have increased the need for energy efficiency. Resources in manufacturing facilities need to be used in the most efficient way.

The increasing use of computer-based tools for supporting production planning and control, as well as management and control of energy systems, has not been as beneficial as might first appear. These two types of tools are seldom integrated, which complicates the control of either system. A methodology for analysing the production system, the energy system and these systems interaction with each other, will enhance the possibility of improved control of the facility.

This research has focused on formulating a methodology for more efficient use of energy in manufacturing plants, with main focus on electricity use. The methodology uses Discrete Event Simulation (DES) as a tool for applied analysis of manufacturing systems. Focus area of the study has been on the energy intensive foundry industry. The methodology aids the process of efficient working by identifying what processes are important, what activities have to be carried out and what types of analyses can be undertaken. A way to categorise equipment by energy usage is presented to simplify the procedures of collecting, presenting and using data in the simulation model. An approach to how the model can be built is described so that the simulation model can be used for analysis of energy use.

To evaluate the methodology four case studies were carried out at different foundries in Sweden. It was found that the level of maturity between the different companies at the outset of the research project varied, regarding manufacturing and simulation as well as energy use. These differences enhanced the analysis in the way that specialised solutions had to be made to complete the analysis. The output from the simulation case studies showed that there is potential to reduce both electricity and power use in all foundries studied.

The methodology, and the integration of Discrete Event Simulation, complements the use of energy models for industrial applications, since analysis can be made on the discrete production which is mimicked by the model. The range of applications that utilise Discrete Event Simulation in industry is also enhanced. The research study has successfully shown that energy data can be added to a simulation model and that the model can be built in a way that makes it useful for analysis of both production efficiency and energy use. The methodology presented can help companies reduce their overall energy use and peak power loads. This will not only reduce the total energy related costs for the companies but also the CO_2 emissions, reducing the companies' overall environmental impact.

To extend the methodology future research will be conducted to add optimisation techniques to the simulation models and to integrate the models with surrounding systems, such as Enterprise Resource Planning (ERP) systems and Load Management Systems (LMS). Future investigation is also needed to determine whether the methodology can be used for dynamic Life Cycle Assessments (LCA) where the production will contribute to the impact a product will have on the environment during its whole life cycle.

II. Abstract in Swedish

Sammanfattning

Marknadens krav på tillverkarna tvingar dessa att ständigt förbättra sina produktionssystem genom att öka flexibiliteten och kvaliteten och sänka tillverkningskostnaderna. Genom att använda simuleringstekniker kan man öka kunskapen om sitt produktionssystem och alternativa lösningar kan testas. Simulering har därför spelat en stor roll i senare års industriella utveckling. Det utvecklas ständigt nya simuleringstekniker och nya sätt att använda dessa.

På grund av de, historiskt sett, låga energirelaterade kostnader, i förhållande till övriga Europa, har dessa kostnader ofta haft lägre prioritet inom svensk industri. Utvecklingen på energimarknaden och osäkerheten runt framtida energipriser har ökat betydelsen av energieffektivisering. Alla resurser i ett produktionssystem måste användas på det mest effektiva sättet.

Den ökande användningen av datorbaserade hjälpmedel för såväl produktionsplanering och styrning som hantering och styrning av energisystem har inte alltid varit till lika stor hjälp som det var tänkt. Dessa två typer av system är sällan integrerade med varandra vilket istället komplicerar för användandet av båda systemen. En metod för att analysera produktionssystemet, energisystemet och deras inbördes relationer kommer att öka möjligheten att styra anläggningen på ett bra sätt.

Denna forskning har fokuserat på att formulera en metodik för att använda energi och effekt mer effektivt i tillverkningsanläggningar, med huvudfokus på elanvändningen. Metodiken använder Diskret Händelsestyrd Simulering (DES, från engelskans Discrete Event Simulation) som ett verktyg för att analysera produktionssystem. Studien har fokuserat på den energiintensiva gjuteriindustrin. Metodiken hjälper till att identifiera vilka processer som är viktiga, vilka aktiviteter som måste genomföras och vilka typer av analyser som kan genomföras. Ett sätt att kategorisera utrustning efter energianvändningen presenteras för att förenkla datainsamlingen, användandet av dessa data i modellen och presentation av resultat. Ett tillvägagångssätt för hur modeller kan byggas för att användas till energianalys beskrivs.

För att utvärdera metodiken har fyra fallstudier genomförts på fyra olika gjuterier i Sverige. I början av forskningsprojektet identifierades skillnader i kunskap kring produktions- och energifrågor mellan de olika medverkande företagen. Dessa olikheter har tvingat fram speciallösningar som har utökat forskningen och förbättrat analyserna. Utfallet från simuleringsfallstudierna visade att det finns potential att reducera såväl energianvändningen som effektuttaget i alla studerade anläggningar.

Metodiken, genom integrationen av Diskret Händelsestyrd Simulering, kompletterar den mängd av energimodeller som finns och används inom industrin idag, då analyser kan göras på diskret produktion. Den ger också utökade möjligheter för användandet av Diskret Händelsestyrd Simulering i industrin. Forskningen har visat att det går att addera energidata till en simuleringsmodell så att den går att använda för analys av både produktions- som energieffektivitet. Metoden som presenteras kan hjälpa företag att minska sin energi- och effektanvändning. Detta kommer inte bara att minska energirelaterade kostnader för företaget utan även CO_2-utsläppen som minskar företagets klimatpåverkan.

För att utöka metodiken kommer forskning att genomföras för att addera optimeringstekniker till simuleringsmodellen och att öka integreringen med omgivande system såsom ERP-system och effektstyrningssystem. Ytterligare undersökningar behövs för att avgöra om metodiken kan användas också för dynamisk livscykelanalys, där produktionen bestämmer vilken påverkan en produkt har på miljön under sin livscykel.

III. Acknowledgements

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V. Nomenclature and list of acronyms and abbreviations

3D	Three Dimensional
AutoMod	The name of a DES program from Brooks Automation, Inc.
CAD	Computer Aided Design
CAR	Computer Aided Robotics
CFD	Computational Fluid Dynamics
COTS	Commercial-Off-The-Shelf
COVERT	Cost OVER Time
CR	Critical Ratio
DES	Discrete Event Simulation
DRCA	Dynamic Rough Cut Analysis
ECS	Electricity Certificate System
ED	Enterprise Dynamics, a DES program from Incontrol Enterprise Dynamics
EDD	Earliest Due Date
EMS	Energy Management Systems
ERP	Enterprise Resource Planning
ETS	Emission Trading Scheme
FDM	Finite Difference Method
FEM	Finite Element Method
GDP	Gross Domestic Product
GUI	Graphical User Interface
HVAC	Heating, Ventilation, Air-Conditioning
IA	Immune Algorithms
IMTI	Integrated Manufacturing Technology Initiative
IMTR	Integrated Manufacturing Technology Roadmapping project
IV&V	Independent Verification and Validation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment or Life Cycle Analysis
LCC	Life Cycle Cost
LMS	Load Management System
LP	Linear Programming
LPG	Liquefied Petroleum Gas
MILP	Mixed Integer Linear Programming

MIND	Method for analysis of INDustrial energy systems
MOFLP	Multi-Objective Fuzzy Linear Programming
M&S	Modelling and Simulation
ODBC	Open DataBase Connectivity
OPC	OLE for Process Control (where OLE means Object Linking and Embedding)
PFE	Programme for improving energy efficiency in energy-intensive industries (in Swedish: Program För Energieffektivisering)
SEA	Swedish Energy Agency (in Swedish: Energimyndigheten)
SFA	Swedish Foundry Association
SME	Small and Medium-sized Enterprises
SMART	Simple Multi-Attribute Rating Technique
SPT	Shortest Processing Time
TOE	Tonnes of Oil Equivalents
WSC	Winter Simulation Conference

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1 Introduction

1.1 Research background

1.1.1 Towards energy efficient manufacturing

Considering the competition in today's industry there are obvious reasons for working with continuous improvement. Companies need to be able to adapt to new situations, including also changes in laws, taxes and raw material prices. Several approaches, technologies and working methods for adapting to these situations have emerged during the evolution of the industrial society, computer simulation and energy modelling being two of these. These approaches, technologies and working methods are developed not only with the intention of improving the technology itself but also extending usage of the technologies. Altogether, the ultimate goal is to use all resources in the most efficient way, whether it be energy or others, such as human resources or various materials.

1.1.2 Using simulation

Simulation as a technique has an almost unique potential for improving processes [IMTR 2000]. However, using models of a real system for simulation is a delicate task. A model needs to be thoroughly verified and validated to ensure that it is a good representation of the real system. Using a structured approach to carrying out a simulation study is therefore important and in recent years several researchers have presented their methods with their own views on how a simulation study should be conducted [Banks et al. 2005] [Jägstam 2003] [Law 2007] [Musselman 1994] [Pegden et al. 1995] [Pidd 2004] [Robinson 1994] [Watkins 1993].

Previously when Discrete Event Simulation (DES) has been applied, it was merely used for validating ideas, calculating throughput and analysing bottlenecks. However, it has become clear that simulation can be used at all stages of the evolution of a company, from investment analysis to operational planning. With the increase in computer power, calculation time is no longer a barrier as regards fast results and implementation. Additionally, the evolution of the simulation programs and their ability to communicate with other programs is an important step towards an integrated environment in which the simulation program is a tool for frequent analysis of manufacturing systems. Furthermore, development towards more large-scale models will force program developers to enhance the functionalities in the simulation programs [Barton et al. 2003]. There will also be an increase in integration with other processes such as process planning [Banks et al. 2003]. With the increased use of simulation the user base will grow, adding more types of users, who will demand more user friendly simulation programs [Banks et al. 2003] [McLean and Leong 2001].

1.1.3 Incentives for energy efficiency

The nature of the European electricity market has had a dramatic impact on Swedish companies. Since the turn of the century, electricity prices have rapidly increased several-fold for a normal industrial user. The exact figures differ significantly depending on the size of the company, since the prices are lower for large users and vice versa.

Most companies in Sweden are small (less than 50 employees) or medium-sized (50 to 250 employees) [Swerea SWECAST 2007b] with modest knowledge of how the electricity market works. Less than half of the companies have a strategy for working with energy efficiency [Thollander 2008]. As a consequence, the companies also have a limited ability to stand up against the "big three" (Vattenfall, E.ON and Fortum), who produce 87 percent of the electricity in Sweden today [SEA 2007b]. Different means of control have been introduced in the electricity market. The European Union Emission Trading Scheme (EU ETS) [EU ETS 2007], Electricity Certificate System (ECS) [SEA 2006b] and Programme for improving energy efficiency in energy-intensive industries (PFE) [SEA 2007d] are three means of control which have been introduced with the aim of encouraging the reduction of CO_2 emissions, increasing the use of green energy and encouraging energy efficiency activities. With the global climate situation it is difficult to question the intentions of these means of control, even though scientists argue that there may be better ways to achieve these aims. However, for a small electricity buyer, the situation has become even more complicated with these additional external forces.

The foundry industry is one of the most energy intensive industries. Not only is energy a substantial expense when producing castings, unrestricted access to energy, mainly electricity, is important for the quality of the castings. Unforeseen interruptions to the supply of energy, for melting in particular, can cause uneven quality due to excess formation of slag as well as unwanted chemical reactions that cause unwanted material structures. To avoid these problems many foundries in Sweden have decided to have high load subscriptions and to accept the associated higher cost. In the past these higher costs, still relatively small in comparison to other costs, have not been a major problem. However, with increased electricity and power load costs it has proven to be a costly approach. Installing Load Management Systems (LMS) is a way to keep track of the load, but many users have found it difficult to find a good way to prioritise equipment to force down the supply when needed. Forcing down the supply for a melting furnace for example can, as previously mentioned, result in material problems.

1.1.4 The Swedish foundry industry

With almost 200 companies and some 10,000 employees the Swedish foundry industry has an aggregate domestic turnover of 1.3 billion Euros. Swedish foundries produce some 354,000 tonnes of castings annually of which 74% are iron castings, 19% non-ferrous castings and 7% steel castings [Swerea SWECAST 2007a]. By way of comparison, the total production of castings in Europe in 2005 was 16,557,000 tonnes [CAEF 2006]. Germany is the largest producer in Europe with 5,108,000 tonnes followed by Italy with 2,541,000 tonnes. The largest producer in the world, China, produced 22,420,000 tonnes in 2005 and the second largest, United States, produced 12,314,000 tonnes [CAEF 2006].

Swerea SWECAST is the research and development institute of the Swedish foundry industry. The institute has approximately 45 employees with different specialist competences. Swerea SWECAST also administers the industry organisation called Swedish Foundry Association (SFA) which has almost 200 members among foundries, suppliers and buyers of castings. The author of this thesis is currently employed by Swerea SWECAST.

This research was conducted within a research programme sponsored by the Swedish Energy Agency (SEA) (Energimyndigheten) [SEA 2007a] called "Energy research programme for the foundry and manufacturing industry". The aim of the programme is to identify, develop and implement energy-efficient foundry technologies and working methods and to increase knowledge of them and also to create incentives for applying them within the Swedish foundry industry.

1.2 Research aim and objectives

The aim of this research study is to create a methodology for improved energy management of industrial plants through the use of Discrete Event Simulation (DES) in the production planning and control process. Focus of the studies will be on electricity use and the use within the electricity intensive Swedish foundry industry.

Application of the methodology should help increase awareness of the plant and improve plant control, resulting in decreasing electricity use and more efficient production. It will also help companies analyse the impact of new investments and reorganisation of facilities.

Additionally, the methodology should be sufficiently generic to be applicable to companies in other electricity intensive industries using similar resources to those in the foundry industry.

1.3 Scope of the work

It is not possible to devise a solution applicable to all types of industrial applications. Therefore, the targeted domain for the application proposed in this research study is foundries in Sweden. The SEA considers foundries in Sweden to be energy intensive [SEA 2007c] and therefore solutions for more energy efficient casting are required to make the foundry industry more cost efficient. Companies in Sweden are limited by rules and regulations that sometimes differ from those in other countries. Prices and taxes also differ.

Foundries use electricity to a large extent for most processes, especially the most energy-intensive production processes such as melting, holding and moulding.

Electricity has therefore been the primary focus of attempts to minimise energy use. In this thesis the word *energy* is used to describe the general use of energy, independent of the source. Furthermore the word *electricity* is used when describing the specific use of electricity as an energy source and *power* is used to describe electrical load.

The methodology presented in this work uses historical electricity data based on the actual electricity use within the system studied. Many systems have tools for reuse of heat, for example from ventilation and water cooling. These types of systems have not been considered because of their interaction with for example the outside weather conditions and the structure of the buildings which can not be measured and modelled in a DES model in a useful way. These systems, however, will reduce electricity use, as shown by the historical data used.

The analyses using simulation in this work have been carried out using Discrete Event Simulation (DES) and Commercial-Off-The-Shelf (COTS) programs for DES.

1.4 Research approach

The main areas of research undertaken are described in chapter 2. The areas of focus in the literature review are used as the basis for the subsequent research study. Information gathered from the literature review is used in formulation of the methodology proposed which is then tested on case studies in the foundry industry. Results are analysed and conclusions are drawn, formulating the contribution to knowledge. Figure 1 describes the research method and literature review and the relation between different parts of the thesis.

1.4.1 Literature review

A comprehensive literature review has been carried out within areas of importance to the topic of this research study:

- Energy use and energy management of industrial environments.
- Computer simulation technology and industrial applications.

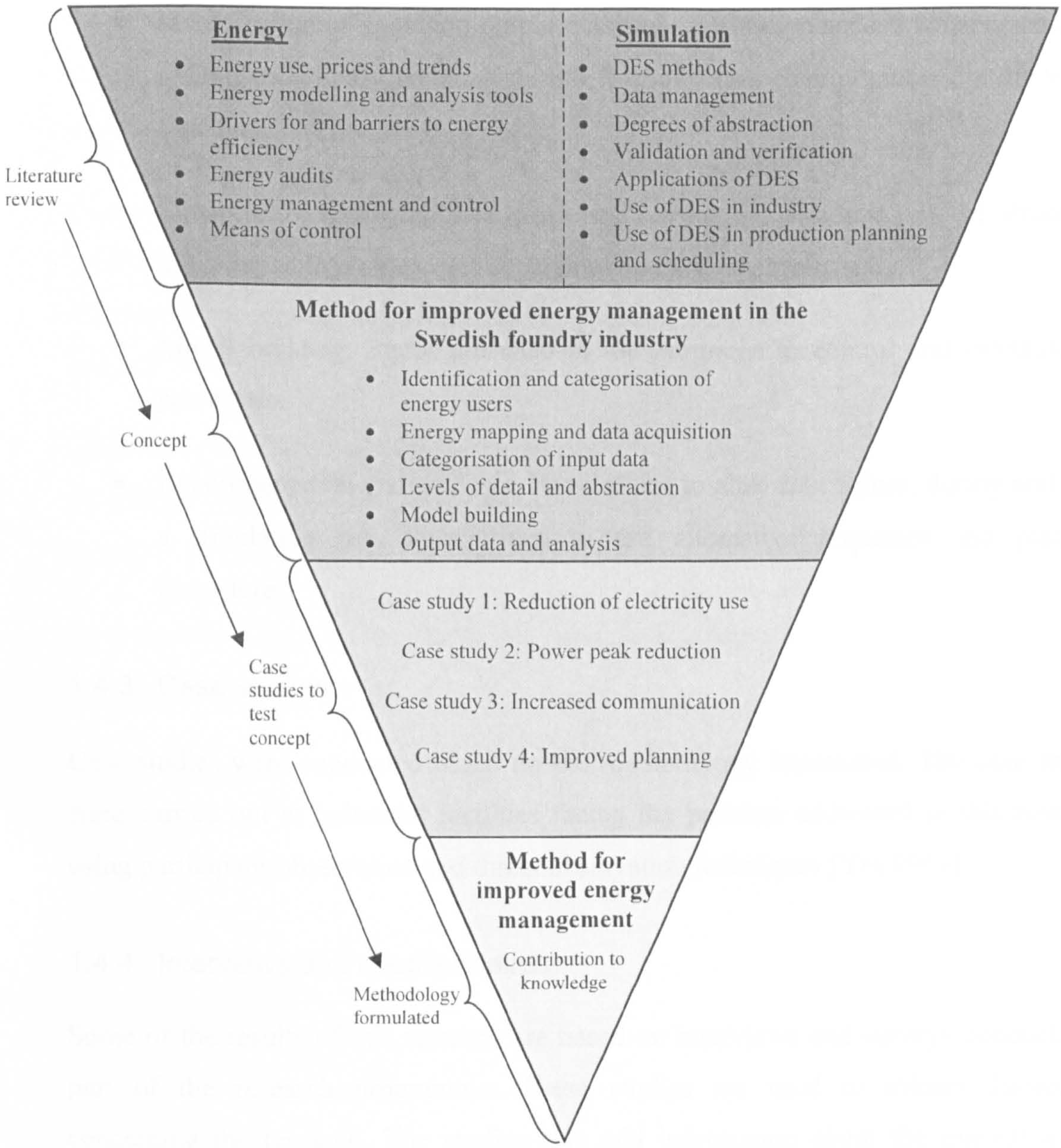


Figure 1. Research method and literature review and the relation between different parts of the thesis.

1.4.2 Conceptual methodology development

Based on the literature and technical reviews conducted, a conceptual methodology has been formulated. This conceptual methodology addresses identified problems and describes the methodology in a wide perspective with conceptual solutions for how problems can be solved in practice. Main parts of the conceptual solution are:

- Identification of input and output data and information needed when conducting a simulation study for analysis of electricity use. Energy audits are made and historical data are used.

- Structure for managing data inside and outside the simulation model. Processes are grouped into categories depending on their electricity use.

- Model building. States are used in the programs to control and calculate the power use.

- Experimentation and analysis. Possibilities to alter data before, during and after a simulation run. Possibilities to use alternative processes and planning procedures.

1.4.3 Case studies

Case studies were conducted based on the methodology formulated. The case studies were carried out at industrial facilities facing the problem addressed in this research, using participant-observation and direct observation techniques [Yin 1994].

1.4.4 Interviews and questionnaires

Some of the results of this research are based on interviews and surveys conducted as part of the research programme. These studies are used to inform discussions concerning the research. The studies also add information about the interest in and possible implementation of the work within the foundry industry in both the near and medium term.

1.5 Thesis structure

Chapter one, this chapter, provides an overview of the thesis including the research background, aim, objectives and boundaries.

Chapter two presents the research methods followed in this study. Theories about scientific methods and case study research are described.

Chapter three describes how the energy and the electricity markets work and shows the importance of energy efficiency. This chapter also describes different methods for working with energy efficiency and energy management.

Chapter four defines the theories and applications of simulation. It describes how simulation can be and is currently used in industry. Other application areas of simulation are mentioned and simulation methods are described together with related research issues.

Chapter five is a central part of this thesis and describes the methodology formulated for energy management using modelling and simulation. Key modelling and simulation solutions are presented.

Chapter six describes four industrial case studies carried out to evaluate different aspects of the methodology.

Chapter seven concludes the work by discussing the results and points out areas for further research.

2 Research method

This chapter includes the scientific methods chosen and the theories on which they are based. However, it is important to bear in mind that there is no right or wrong in the choice of research approach and that all theories have advantages and disadvantages that make them more or less applicable to different application and problem domains. Described here are the scientific methods that the author believes are most relevant to the research.

Early in the research process it was decided that case studies would play an important role in the research approach. Case studies were to be conducted at plants representative of the scope of the research. Interviews and questionnaires add additional support to the discussions and show the relevance of the research from the point of view of the industry.

2.1 Scientific research method

A researcher's goal is to formulate questions and to find answers to them. Dane [1990] states that no one can ask all the questions and no one can find all the answers to any one question. Dividing the goals of the research into five subcategories provides a more concrete approach. These subcategories are *exploration, description, prediction, explanation* and *action* [Dane 1990]. Industrial research as described in this research has the character of action research but simulation itself is of a predictive nature. A simulation model is, in general, developed to make a prediction of the future by using historical information.

The scientific method follows a general process, as described, for example, in Spata [2003], see Figure 2. In general terms it illustrates the main steps in a scientific study. Starting with a hypothesis, tests are completed, analysis is made and conclusions are drawn which either answer the question or define further research. Bryman [2001] shows a similar process but restricts the approach to include only deductive studies. Deduction is together with induction the two ways on which scientists can draw conclusions. These are somewhat contradictory to each other and are useful in different situations. Deduction is the most common view of research. The researcher uses the information within a domain to define a hypothesis. The scientist must define how data can be collected to make an analysis. With the appropriate data, conclusions can be drawn that either confirm or reject the hypothesis. Induction is a research method where the researcher draws generalised conclusions from research and defines the theory from these. An inductive study is often followed by a deductive one, where the theory is tested to see if it holds with alternative data. In that case it becomes an iterative process as well. [Bryman 2001] [Patel & Tebelius 1987]. Most applied simulation research is inductive.

Casual observation → Generating a hypothesis ←
↓
Testing the hypothesis (experimentation)
↓
Analysing the data
↓
Drawing conclusions
↓
Refining the hypothesis
↓
New ideas

Figure 2. Steps in the research process. [Spata 2003]

2.2 Case studies

As mentioned earlier, the research presented depends to a large extent on case studies. Yin [1994] describes *case studies* as one of five major strategies for doing social science research. *Experiments*, *surveys*, *archival analysis* and *histories* are the other four. Case studies as a research strategy are preferred when *how* and *why* questions are being addressed, when the researcher has little control over the events and when the focus is on contemporary events [Patel & Tebelius 1987] [Yin 1994].

2.2.1 Designs for case studies

There are four different designs for case studies as described by Yin [1994] – *single case holistic designs*, *single case embedded designs*, *multiple case holistic designs* and *multiple case embedded designs*. The single case study can be appropriate during some circumstances. It is, however, important to analyse the possibilities that the results may be misleading and not representative. The holistic design addresses one general issue while the embedded design may address the general issue as well as a subunit or other connected issues. The case studies on which the results in this research study are based originate from multiple case embedded design studies.

2.2.2 Types of case studies

Case studies can be divided into three different types – *exploratory, descriptive* and *explanatory* [Yin 1993]. Exploratory case studies are those that Yin [1993] says have given case studies the notorious reputation of being "sloppy". In an exploratory case study, fieldwork and data collection are undertaken prior to final definition of the study question and hypothesis, and intuition can have an impact on the research. A descriptive case study, as its name implies, is a description of the object studied. An explanatory case study presents cause-effect relationships, explaining which causes produce which effects [Yin 1993]. The case studies undertaken as a foundation for this research are a combination of exploratory and explanatory case studies.

2.2.3 Criteria for judging the quality of research designs

It is possible to judge the quality of a research design by means of certain logical tests. Concepts that have been offered for these tests include trustworthiness, credibility, conformability and data dependability [US GAO 1990] [Yin 1994]. Four tests are commonly used to establish the quality of empirical social science. Since case studies can be considered a type of empirical study, the tests are also relevant to case studies. The tests are [Yin 1994] [Kidder and Judd 1986]:

- **Construct validity**, which deals with establishing correct operational measures for the concepts being studied. Critics point to the fact that case study investigators fail to develop sufficient operational sets of measures and that subjective judgements are used to collect data. Three tactics are used to increase construct validity. The first is to use multiple sources of evidence, the second to establish a chain of evidence and the third to have the draft case study report reviewed by key informants.

- **Internal validity**, which is a concern only for causal or explanatory case studies, where the investigator is trying to show that a certain event leads to another event. The strategies to establish internal validity are to perform pattern-matching, explanation-building and time-series analysis.

- **External validity**, which deals with the problem of knowing whether a study's findings can be generalised. The way to increase external validity is to use replications with several case studies.

- **Reliability**, where the goal is to minimise the errors and biases in the study and ensure that the same case study can be repeated following the exact same procedures as before arriving at the same findings and conclusions. This can be achieved by case study documentation.

2.2.4 Selection of cases

When selecting case studies it is useful to try to select cases which are typical or representative of other cases. Sometimes a typical case works well but it may also be so that unusual cases help illustrate matters that may be overlooked in typical cases. The first criterion should therefore be to maximise the outcome and to choose cases that are most likely to lead us to understanding, assertion and generalisation. It is also important to bear in mind that not all cases will work out well. It is therefore important to make some early assessment of progress to see if a specific case should be dropped and another selected. [Stake 1995]

2.2.5 Collecting the evidence

Merriam [1998] points out that case studies, unlike the other strategies, do not claim particular methods for data collection and analysis but that any method can be used. Stake [1995] adds that there is no particular moment when data gathering starts. It begins even before there is a commitment to conduct the study via acquaintance with other cases, background information and first impressions.

Data collection for case studies can rely on several different sources of evidence. Yin presents the six major sources of evidence that are most common [Yin 1994]. These are *documentation*, *archival records*, *interviews*, *direct observation*, *participant-observation* and *physical artefact*. The sources of evidence that are used in the research presented are documentation, interviews, direct observation and participant-observation.

2.3 System analysis

A majority of the work within this research is based on case studies of production systems and their corresponding energy systems. System theory and system analysis in a wider perspective are described in [Checkland 1999] [Churchman 1968] [Ingelstam 2002]. Churchman [1968] describes five considerations that must be kept in mind when reasoning about a system:

1. The overall goals of the system and the performance measures.
2. The environment of the system: the fixed constraints.
3. The resources of the system.
4. The components of the system, their activities, goals and performance measures.
5. The management of the system.

Churchman [1968] further says that there are other ways to reason about a system but that the list contains some minimum requirements. However, before being able to reason about a system, the system itself must be defined. Ingelstam [2002] defines a system as:

- *Components* and *connections* between them creating a system as a whole.
- A system *boundary* which is necessary to separate it from the rest of the world.
- *Surroundings* that have an impact on the system but are not a part of the system.

In many applications the system is given prior to the analysis. The criterion is often that, what belongs to the system is what the actor can control. What the actor can not control is considered the surroundings [Ingelstam 2002]. However, researchers within different disciplines consider everything to be connected. System theorists do not deny that there may be connections between practically everything, but point out the necessity to divide the whole into systems and subsystems to make it possible to enable an investigation [Ingelstam 2002].

A system analyst often uses a model of a system to enhance the performance of the human thoughts. Even though a model is used and some calculations are performed using a computer, the analysts should not lose control of the conditions and its inputs and outputs. The system analyst should use the five considerations listed earlier to keep track of the system performance [Churchman 1968].

This research deals with analysis of production systems and energy systems. A production system in this thesis consists of both production processes and support processes. Within the case studies conducted, the system boundary may vary but each has a clear beginning and end. Energy systems in this research study are the energy that has connections to the production system and its processes. The surroundings are, for example, regional energy supply systems, European electricity markets, taxes, fees and other means of control. These surroundings are not part of the studied systems but have an effect on them.

2.4 Summary of research method

This chapter has described the research methods used for conducting the research on which this research study is based. The aim of this chapter has been to help the reader understand how the research has been conducted. The following two chapters, 3 and 4, describes the scientific base on which the used research methods have been applied to.

Scientific research can be divided into several categories depending on the goal of the research and there are several different approaches for conducting scientific research and ways to collect the information needed to draw conclusions. Using case studies can be a good way to test a hypothesis and a system approach is necessary when making an analysis of components with interconnections, a boundary and a surrounding.

3 Energy use

Energy use has increased in the past and is still increasing. A significant component of the energy originates from fossil fuels, which has an impact on global warming. The most effective way to mitigate global warming is energy efficiency. This chapter will describe the problem we are facing and how it can be addressed with the help of research results and methods such as modelling techniques and energy management. Since electricity is the main energy carrier in focus in this research most background information will be about electricity.

3.1 Energy use from a global perspective

The world's aggregated energy use is steadily increasing [Jean-Baptiste and Ducroux 2003]. With the increased use of energy there have also been possibilities for strong economic growth in industrial countries, see Figure 3 [Jean-Baptiste and Ducroux 2003]. But with the increased energy use comes increased use of fossil fuels, which contributes to the increase of CO_2 and other greenhouse gases in the atmosphere and hence to climate change and global warming.

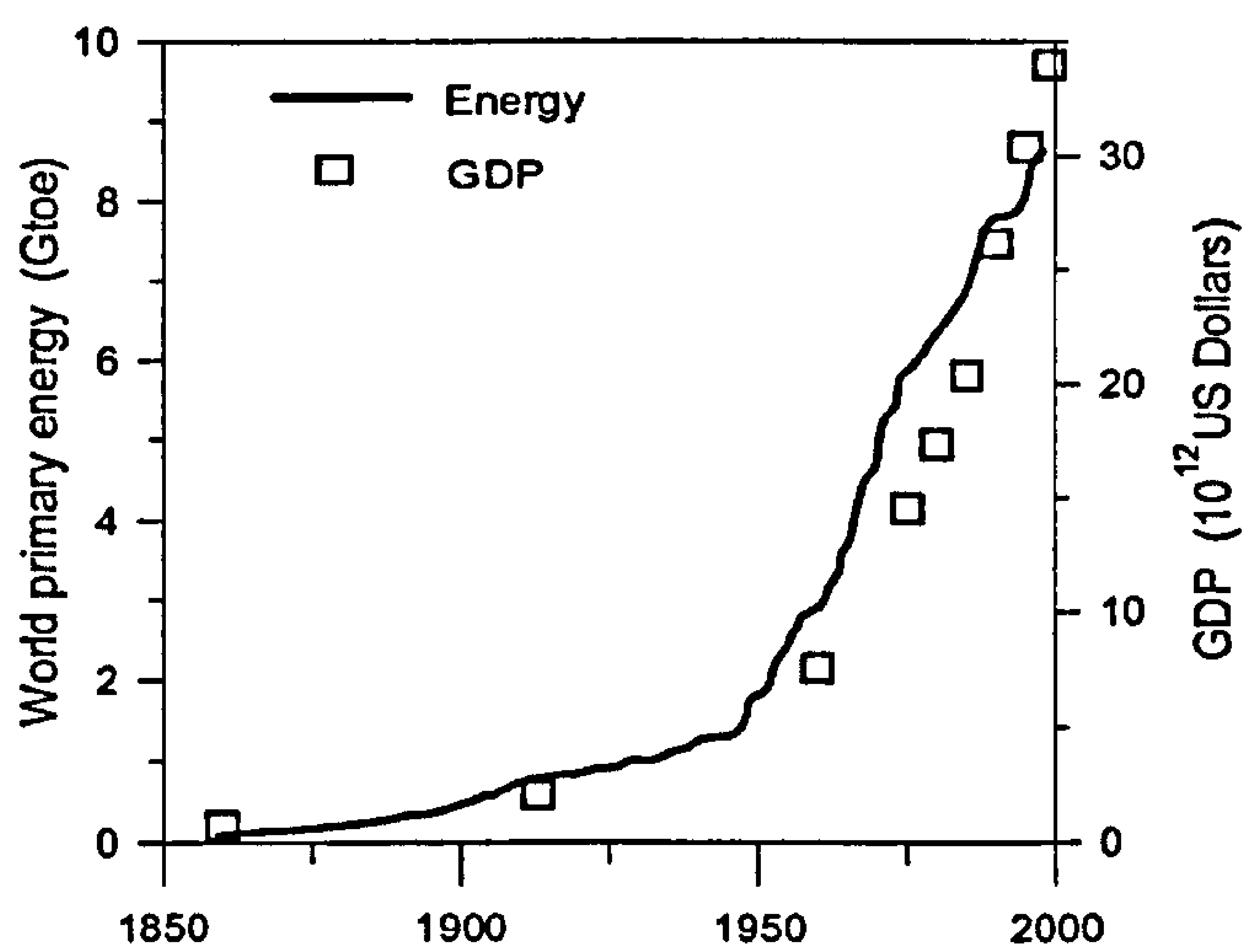


Figure 3. World energy use and GDP. [Jean-Baptiste and Ducroux 2003]

It has been known for a long time that the combustion of fossil energies can cause global warming. Arrhenius [1896] described the issue as early as 1896 and also mentioned it in his book "Worlds in the Making" from 1908 [Arrhenius 1908]. Even though these effects have been known for a long time, it is only during the last decade that it has caught the attention of the public due to scientific evidence of global warming. A report from the OECD [2004] states that energy use is the largest cause of environmental problems in the world. As a result, the Kyoto protocol, first signed in 1997, was initiated to decrease global heating. The agreement says that countries should reduce emissions of greenhouse gases by 5 percent by 2008-2012. The European Union has agreed to decrease the total carbon dioxide discharge by 8 percent by 2008-2012. Another step in the same direction is The European Energy End-use Efficiency and Energy Services Directive which came into force in 2006, proposing a reduction in energy use of 9% in each European member state [COM 2006].

The most cost-effective way to mitigate global warming is to improve energy efficiency [Kamal 1997]. Energy efficiency has already helped to slow down the increase in energy use. In industrial countries there is a decrease in energy intensity, if expressed as Tonne of Oil Equivalent (TOE) per $ of Gross Domestic Product (GDP) [Kamal 1997]. Geller et al. [2006] say that, without the energy efficiency improvements carried out during the last 30 years, the OECD countries would have used 49 percent more energy in 1998 than they did. In developing countries energy intensity is high among those lagging behind in energy productivity, according to Miketa and Mulder [2005]. However, these countries have a tendency to catch up with the developed countries. Cross-country differences seem to be persistent; some will catch up and converge to a steady state while others will fail to catch up. Country-specific factors, such as energy prices, explain some of the cross-country differences [Miketa and Mulder 2005].

3.2 European electricity market

In 2004 the European electricity market was deregulated with the intention of improving the efficiency of the electricity sector and thus also to improve Europe's economy and competitiveness. Common rules have been formulated and the national markets should gradually open up for competition [Directive 96/92/EC].

Due to the market for electricity not being fully free and separate domestic markets with low trading between countries, the prices vary widely between countries in Europe. Figure 4 shows electricity prices in European countries for industrial customers using 2000 MWh/year. There is substantial variation in prices and taxes, where Sweden is among the countries with the lowest prices. Sweden's low prices are due to the high percentage of hydroelectric and nuclear power with relatively low operating costs. In other countries, such as Germany for example, where power plants are mainly fuelled by coal, the prices are higher.

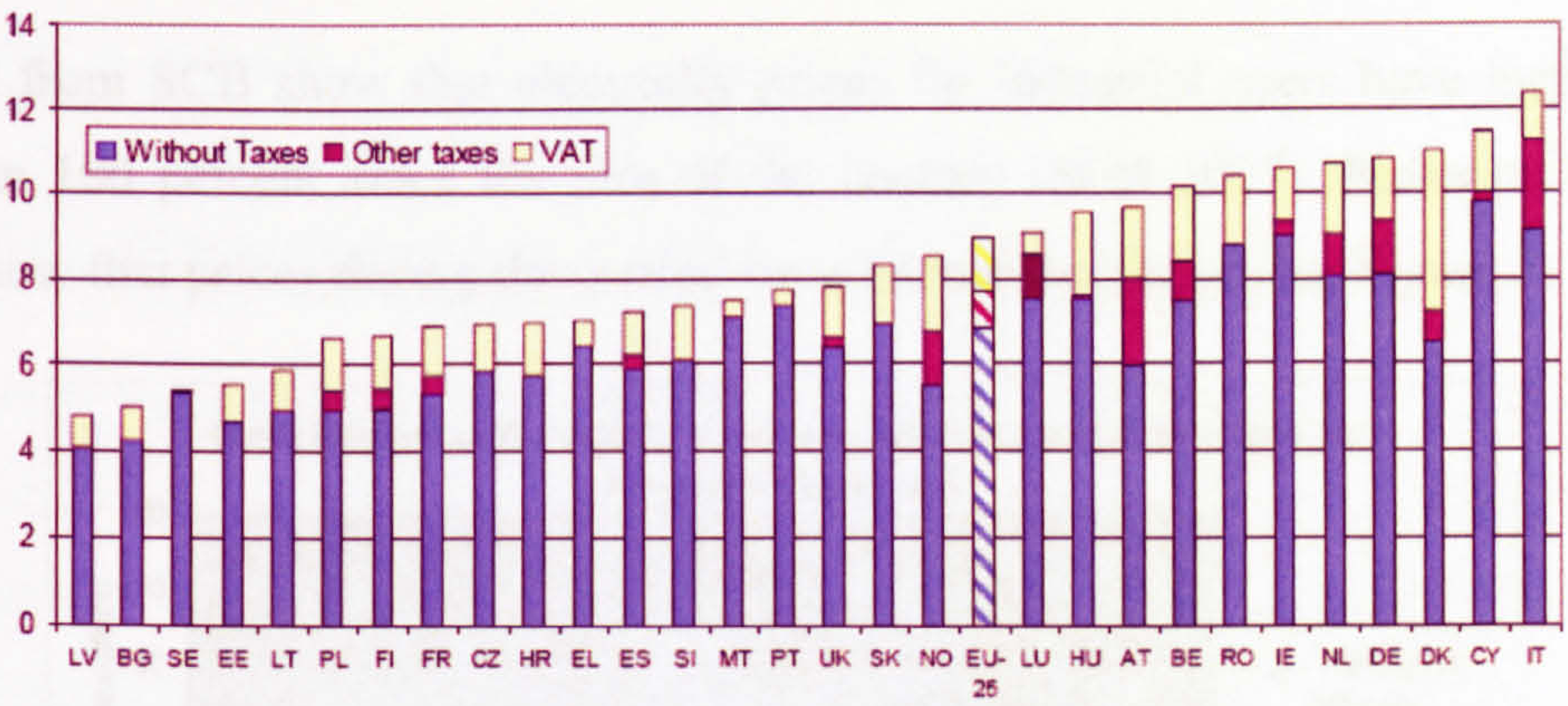


Figure 4. Electricity price for industrial consumers on the 1st of July 2005. Prices in Euro/100kWh for a use of 2000 MWh/year. [Eurostat 2006] (EU25 = weighted average for the following 25 countries: Belgium, Czech Republic, Denmark, Germany, Estonia, Greece, Spain, France, Ireland, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Slovenia, Slovakia, Finland, Sweden and the United Kingdom.)

In the European market the prices will, if the market functions well, move towards marginal cost. This means that in the long run the marginal cost of generation of electricity will even out within the deregulated European market. Due to the low prices in Sweden, Swedish producers of electricity will sell for higher prices to other European consumers leading to higher prices in Sweden and lower prices in other European countries. If there were no limitations on capacity of transfer this would level out the prices in Europe.

3.3 Energy use in industry

The total energy use in Sweden has increased from approximately 457 TWh per year in 1970 to approximately 630 TWh per year in 2005. Of that, industry uses approximately 156 TWh annually [SEA 2006a]. Between 1992 and 2005, Swedish industry's production output increased by 100 percent, while its total energy use increased by 12 percent and electricity use by 15 percent over the same period [SEA 2006a]. This shows that there are efficiency improvements taking place concurrently with productivity increases.

3.3.1 Energy prices

Statistics from SCB show that electricity prices for industrial users have increased by more than 100 percent since the turn of the century [SCB 2007]. Peaks on the price curves show that prices during this period have been even higher, see Figure 5.

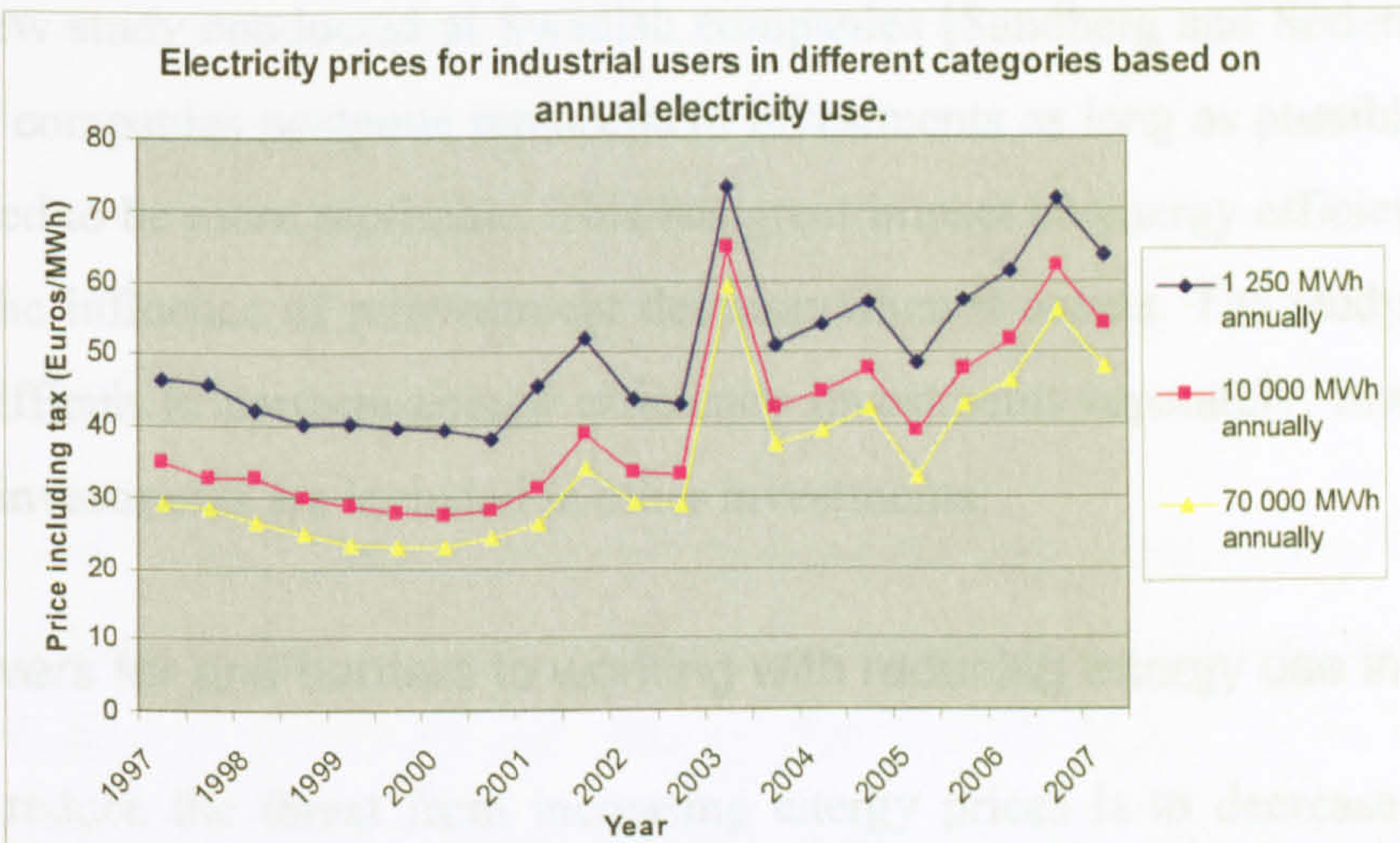


Figure 5. Electricity prices for typical industrial users in Sweden categorized by annual electricity use. The prices include taxes and are based on companies' average cost for all electricity on the first of January and July. [SCB 2007]

3.3.2 Energy efficiency in industry

Boyd and Pang [2000] have shown, through empirical studies, that there is a linkage between energy intensity and productivity. Productivity differences are important determinants of energy efficiency. It is also shown that best practice plants are systematically more energy efficient.

Worrell et al. [2003] describe a study showing that including productivity benefits explicitly in the modelling parameters would double the cost-effective potential for energy efficiency improvements. They also say that it is important to distinguish between the total technical potential for energy savings and the cost-effective potential.

The former describes energy saving potential using state-of-the-art technology, regardless of cost, while the latter also requires a cost analysis to see which savings can be cost-effectively or economically achieved. They also show that implementing state-of-the-art technology is almost twice as expensive as conventional technology. Freeman et al. [1997] further shows that there is a problem when measuring energy intensity. If productivity is included, the indicators will change meaning that there is a discrepancy between value- and volume-based indicators. Therefore, policy makers should be careful when using indicators as a basis for policy decisions.

An interview study conducted at Swedish companies [Sandberg and Söderström 2003] shows that companies postpone replacement investments as long as possible because it is considered to be more profitable. This has great impact on energy efficiency and also enhances the influence of reinvestment decision when it occurs. The study also shows that it is difficult to perform energy efficiency investments separately. Instead, energy efficiency investments are included in other investments.

3.3.3 Drivers for and barriers to working with reducing energy use in industry

A way to reduce the threat from increasing energy prices is to decrease companies' dependence on electricity and other energy sources. However, with some exceptions, resistance to new technologies in Swedish industry is significant. Not only new technology, but also new working methods and aids, simulation being one, are difficult to introduce. Barriers to and driving forces for making production more energy effective as well as guidelines for improvements are described by Rohdin and Thollander [2006a] and Rohdin et al. [2007]. These studies show that there is a great ignorance in industry of the potential of energy saving investments and that the main driving forces are the involvement of one or more key persons in the organization and the existence of a long-term energy strategy. The largest barriers are lack of access to capital, technical risks such as risk of production disruptions, and lack of funding [Rohdin et al, 2007].

One of the drivers for energy efficiency is regulation. It is important that regulation is defined in such a way that the focus is on improving processes to avoid energy inefficiency or environmental pollution. There should be long term goals with increasing levels of regulation and not just regulation for short time fixes [Porter and van der Linde 1995].

One current driver is a tax cut programme formulated by the Swedish government called PFE where companies are given a 55 Eurocents tax reduction per MWh [SEA 2007d]. To qualify for this tax cut the company must have implemented an energy improvement system similar to the environmental management system ISO14001. Some processes, such as metallurgic processes, are already exempted from this tax. The aim of the tax cut is to increase companies' awareness of their own production systems. A reduction of one kWh is equal to the tax for approximately 80 kWh, which is a strong incentive for improving electricity efficiency. Results from the first two years of the programme show that companies have found measures to reduce electricity use by 1 TWh [SEA 2007d]. Many of the investments for achieving these reductions have already been initiated and will be completed during the period of the PFE.

A common view is that there is a trade-off between ecology and economy. On one hand are the social benefits that arise from strict environmental standards and on the other are industry's costs for prevention and cleanup that lead to higher prices and reduced competitiveness. With these arguments there is a struggle between sides, which tends to lead to a step in one direction and then one in the other, depending on the people currently in charge [Porter and van der Linde 1995].

3.4 Energy use in foundries

As described in section 3.2, the deregulation of the European electricity market will cause electricity prices to increase in Sweden. For Swedish companies, this has led to a particularly difficult situation since Swedish energy prices are, and have been for the last decades, among the lowest in Europe. The Swedish foundry industry is, together with other energy-intensive industries, particularly sensitive to higher electricity prices. This is due to their large electricity consumption, their large relative use of electricity compared to the aggregated energy use (see Figure 6) and very high shares of energy costs, 5-15 %, in relation to the added value [Thollander et al. 2005].

3.4.1 Energy intensive processes

In foundries, processing - melting and holding in particular - is the main energy user [Thollander et al. 2005]. The quantity of energy used to melt metal is approximately proportional to the amount of metal molten. The casting yield (the total weight of good castings in relation to the total weight of metal molten) varies from 85 to 95 percent for simple and heavy grey iron castings to 40 to 50 percent for production of small ductile iron castings in mechanised volume production [DETR 1999]. Increasing the yield will immediately lower energy use per time unit. The reduction of scrap is another important issue, which has two effects. First, the energy required for melting is reduced and second, material use, the use of other consumables and the personnel needed are reduced, thus increasing overall capacity. Apart from production processes, such as melting and holding, energy use in the support processes, such as ventilation, lighting and space heating, have often received less attention. One reason for this is the historically low electricity prices [Trygg and Karlsson 2005].

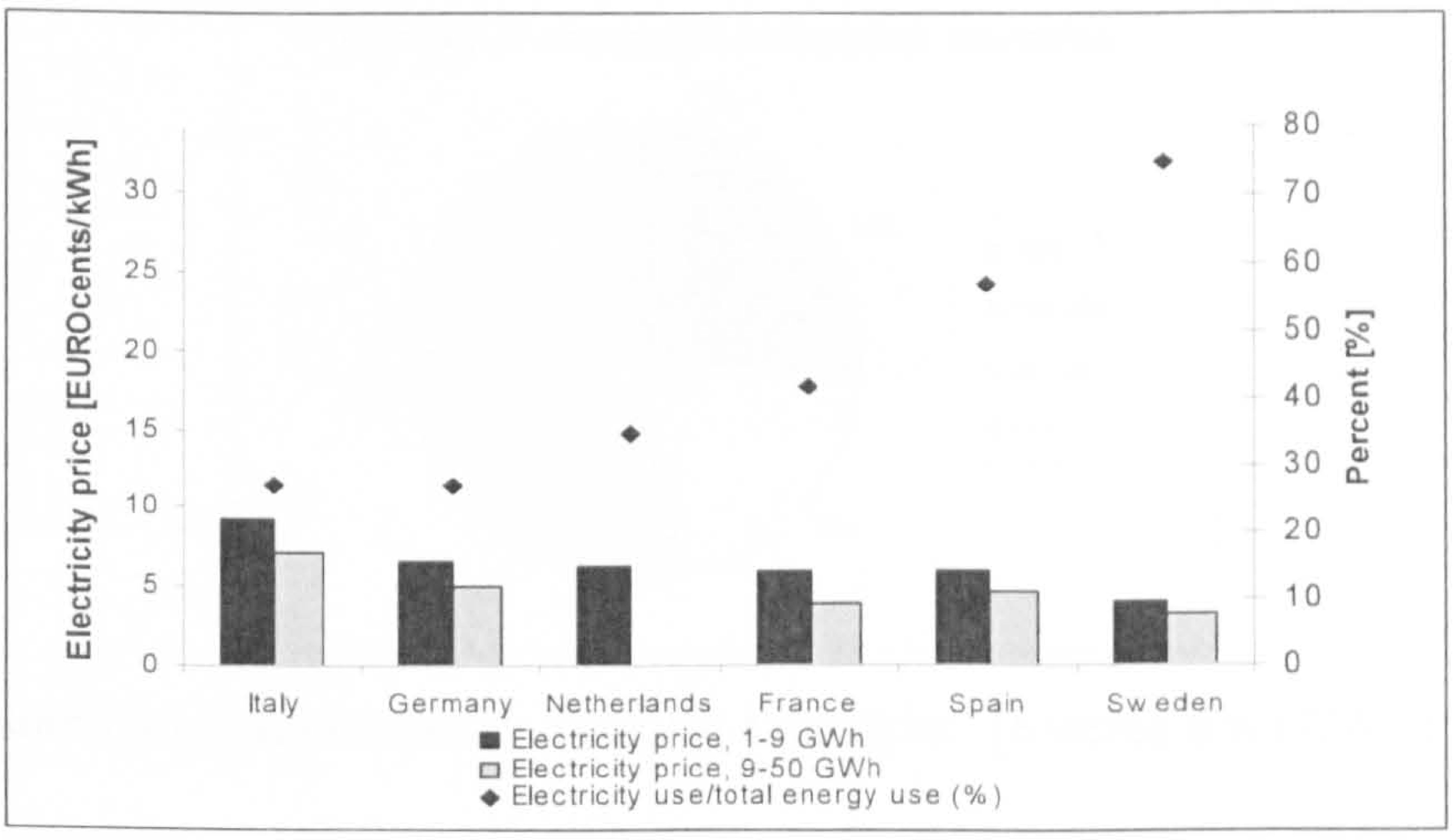


Figure 6. Foundry sector's average use of electricity in relation to the total energy use [%] and the electricity prices for 1-9 GWh and 9-50 GWh enterprises in some European countries. For the Netherlands, too few observations were made in order to state a figure for enterprises using 9-50 GWh annually. [Rohdin et al. 2007]

3.4.2 Energy use and prices

The foundry industry is considered to be an energy and electricity intensive industry. However the use of electricity in the foundry industry in Sweden is fairly low compared to some other electricity intensive industries. The foundry industry uses 278 GWh electricity in comparison to 18,999 GWh in the paper industry, 4,761 GWh in the basic chemistry industr and 5,357 GWh in the steel industry [SEA 2007c]. At the same time, the foundry industry paid 4.1 Eurocents per kWh in comparison to 2.6 paid by the paper industry, 3.0 by the chemistry industry and 3.3 by the steel industry [SEA 2007c]. One reason for the high price is that many foundries are small; 74 percent have less than 100 employees, see Figure 7 [Swerea SWECAST 2007b]. As a consequence, they have less possibility to make a good deal with electricity dealers. There is also a risk of insufficient competence within the companies as regards the energy markets [SEA 2007c].

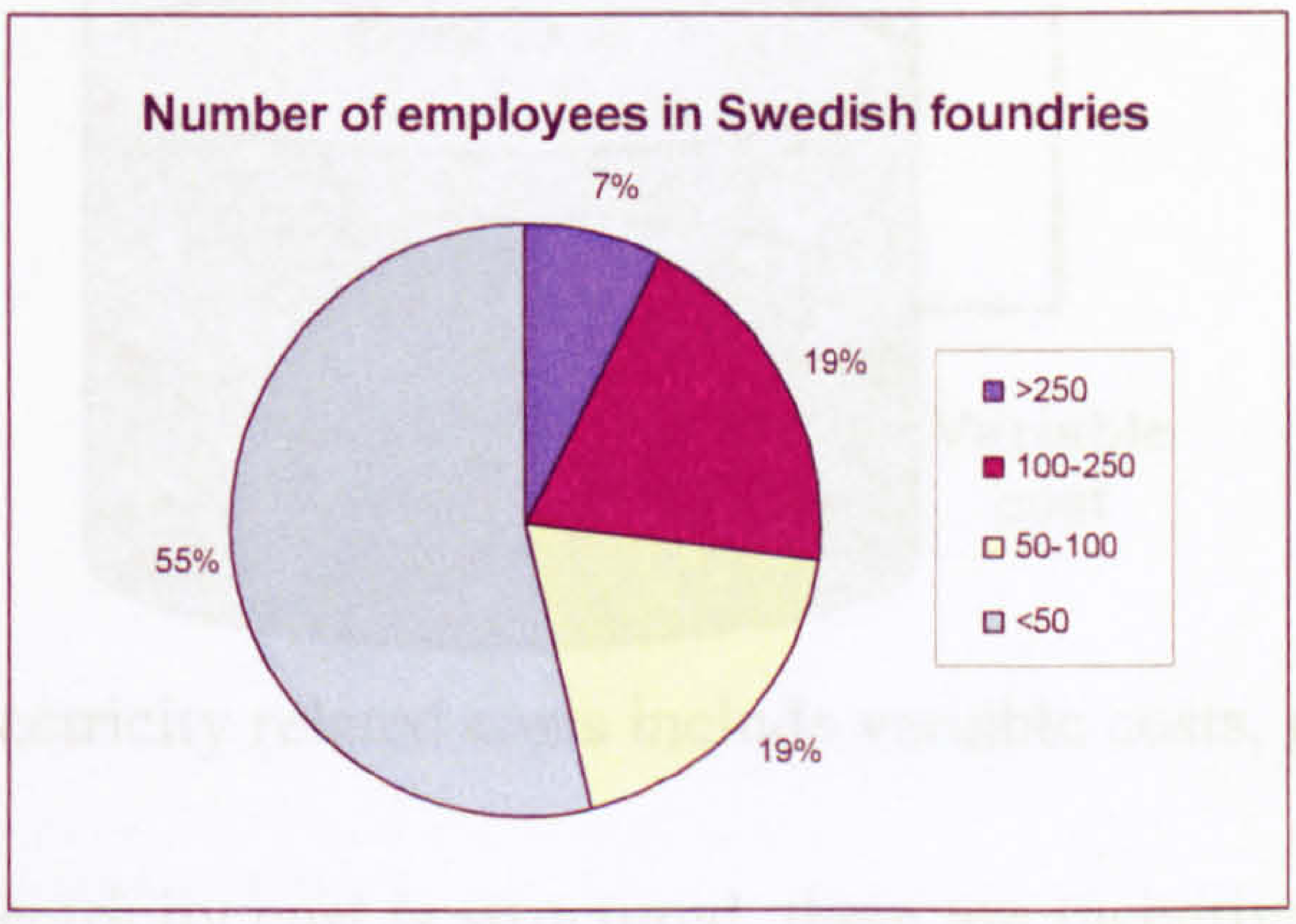


Figure 7. Number of employees in Swedish Foundries. [Swerea SWECAST 2007b]

3.4.3 Load prescription and other limiting factors

The subscription costs for a foundry roughly consist of three parts: *variable electricity cost*, *grid costs* and *taxes*, see Figure 8.

- The **variable electricity cost** is based on the actual electricity use during a period of time. Due to the deregulation of the electricity market the foundries are able to choose from where the electricity is bought, either from the spot market directly, from a power company or from other actors in the market.

- The **grid cost** is set by the owner of the grid and is difficult to change since the market is a monopoly. The grid cost consists in turn of three parts. One is based on the actual electricity use and works like a variable cost, though charged instead by the owner of the grid. The second part is the amount of power subscribed by the company. The third and last part is based on the power used by the company the previous year, where the highest peak load (mean of one hour) decides the amount.
- The electricity **taxes** are currently approximately 55 Eurocents per MWh.

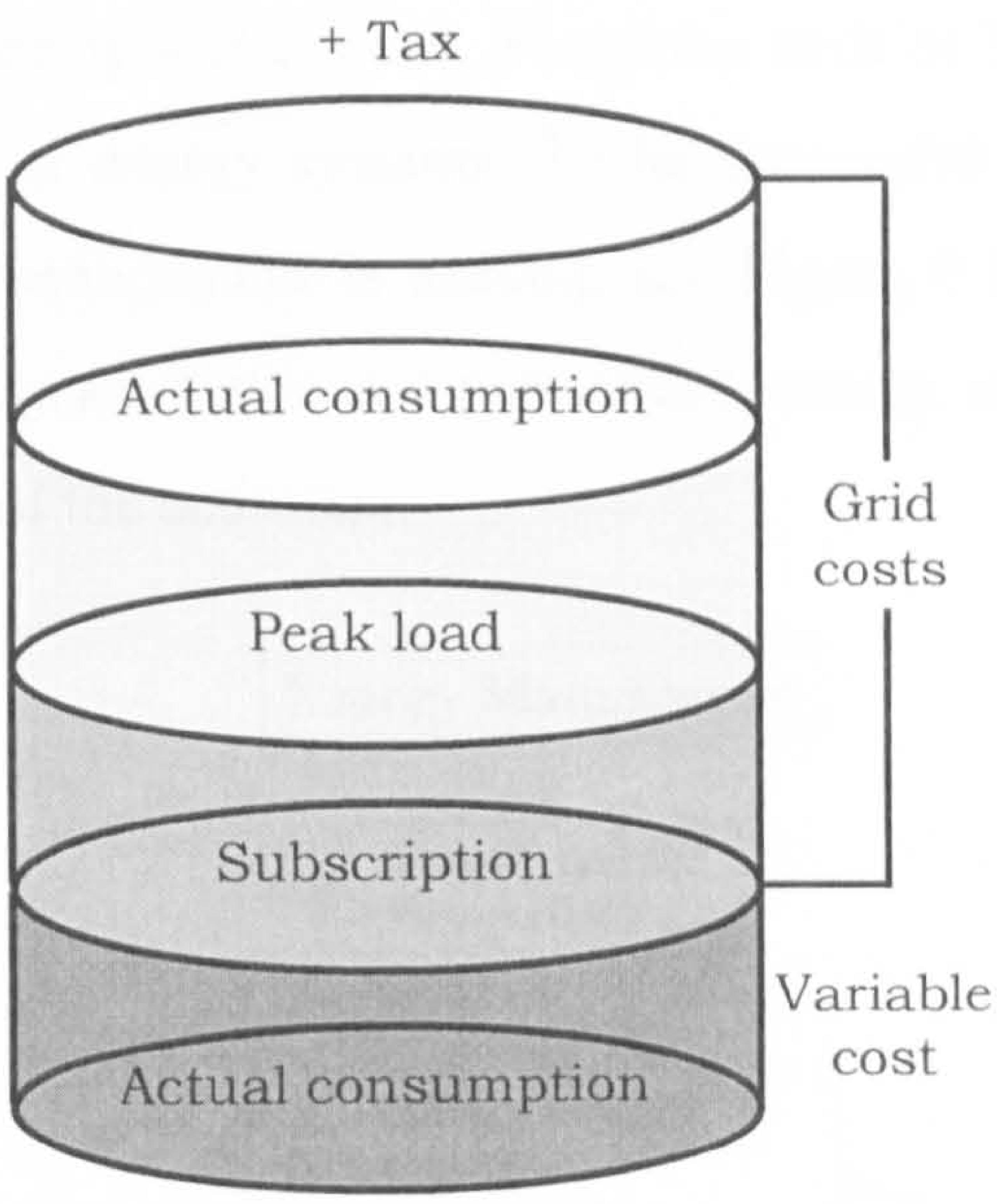


Figure 8. The total electricity related costs include variable costs, grid costs and taxes.

Due to the way the electricity cost is structured, there are incentives not just to keep the actual use to a minimum but also to keep the peak power loads as low as possible. Keeping the peak power loads down will not only reduce the subscription level for the following year it will also reduce the risk of being fined for breaching the subscribed amount the running year. This scheme for electricity subscription is the most common in Sweden today but may vary between companies. With increased integration into the European market there may also be changes in how electricity and power are subscribed. Variations may then also occur daily which is not currently the case in Sweden. This is because the electricity system in Sweden is energy dimensioned as opposed to large parts of continental Europe's electricity systems, which are power dimensioned. In continental European countries the prices are both higher and vary more during the day. Since the Nordic market is small compared to the rest of the markets in Europe it is most likely that the Nordic countries will adapt to European conditions, resulting in higher prices and more variations.

3.5 Energy management

3.5.1 Working with energy management

Energy management is a wide concept and will not be explained in detail. However, energy management in industrial environments often includes some typical activities such as auditing, monitoring and control. Programs such as LMS are used as aids for monitoring and control of energy systems. To be successful in energy management a commitment from top management is needed, see Figure 9 [Kannan and Boie 2003]. There should be clear signals that it is a permanent activity and there should be one or more persons in charge of the activities.

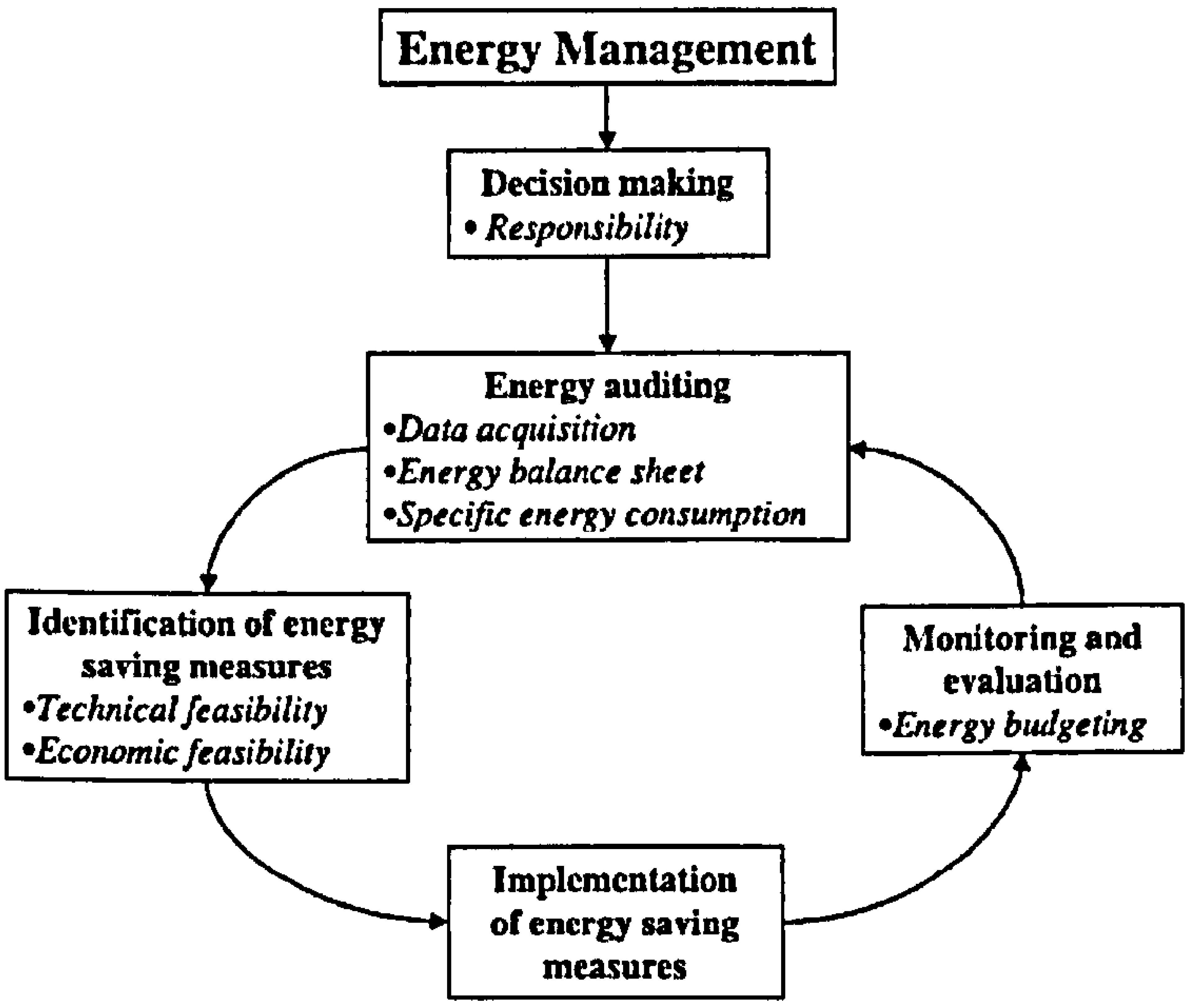


Figure 9. Structure of energy management. [Kannan and Boie 2003]

3.5.2 Load management systems

LMS works mainly through monitoring and control with the aim of reducing the overall energy use and reducing the peak power loads. With an LMS this is done through instant reduction of power to the system when peaks occur, not by planning the production in a better way. The systems can be used to manually identify the reasons for peaks to occur but not often to analyse the interactions between equipment in the production system causing the peaks. This lack of predictive analysis is the main disadvantage of this type of systems.

The range of research within the discipline of energy management and load management is broad. Pal and Huff [2000] describe an energy system where first of all there is a shortage of installed power and secondly that energy purchased is relatively expensive. The management program is continuously updated with information from production and the situation is analysed. There is also an off-line version of the program on which "what if" scenarios can be run and analysed.

The relationship between the end user and the producer and distributors of electricity is an important factor to consider. If the peak load for the producer occurs at different times during the day than for the end user, the end user can experience cuts from the producers' LMS without having a peak, causing unforeseen problems in the production process. With deregulated electricity market there is a possibility to construct specialised rates and tariffs in order to encourage behaviours that are profitable to both the end user and the distributors and producers of electricity [Gustafsson 1998].

3.5.3 Energy audits

Energy audits in industrial environments are generally conducted to get an overview of the energy and power use at company level. The aim is to find ways to reduce the cost through energy efficiency. Even though the objectives of an energy audit are universally accepted, the methods with which they are performed are not standardised [Bhatt 2000]. Many studies show great potential for energy efficiency. However, it is also found that many of the energy efficiency measures are not implemented even though they are found to be cost-efficient. A while after the audit, two important questions can be asked to evaluate the audits: how much energy was saved as a result of the audit and what was the result from an economic viewpoint? [Larsen and Jensen 1999]

Energy audits are carried out to find all types of energy efficiency improvements within a system. The focus is mainly on the equipment and not the relationship between the pieces of equipment. Different energy models are used to analyse relationships. Often it is support processes that have greatest potential for energy efficiency in industry [Trygg 2006]. Idling during day and night operation is one reason, others include losses in compressed air systems, defective equipment, engines that are not correctly dimensioned, and ventilation, lighting and heating that are not optimised.

3.5.4 Classification of energy-using equipment

Classification of energy usage of equipment in manufacturing industry covers two main areas; *production processes* and *support processes* [Trygg 2006], see Figure 10. Production processes are processes that carry out work that has an impact on the final product, while support processes are processes that add no value to the final product. Generally, when seeking to reduce energy, the goal is to reduce the need for support processes as much as possible without losing productivity or degrading the work environment. The goal is also to minimise the use of the production processes, for example by better planning. This broad classification of processes does not tell much about the actual use of a processes and the correlation between them. There are also a number of processes that can be classified as both production and support processes, such as compressed air, which is used for more than one purpose within a company.

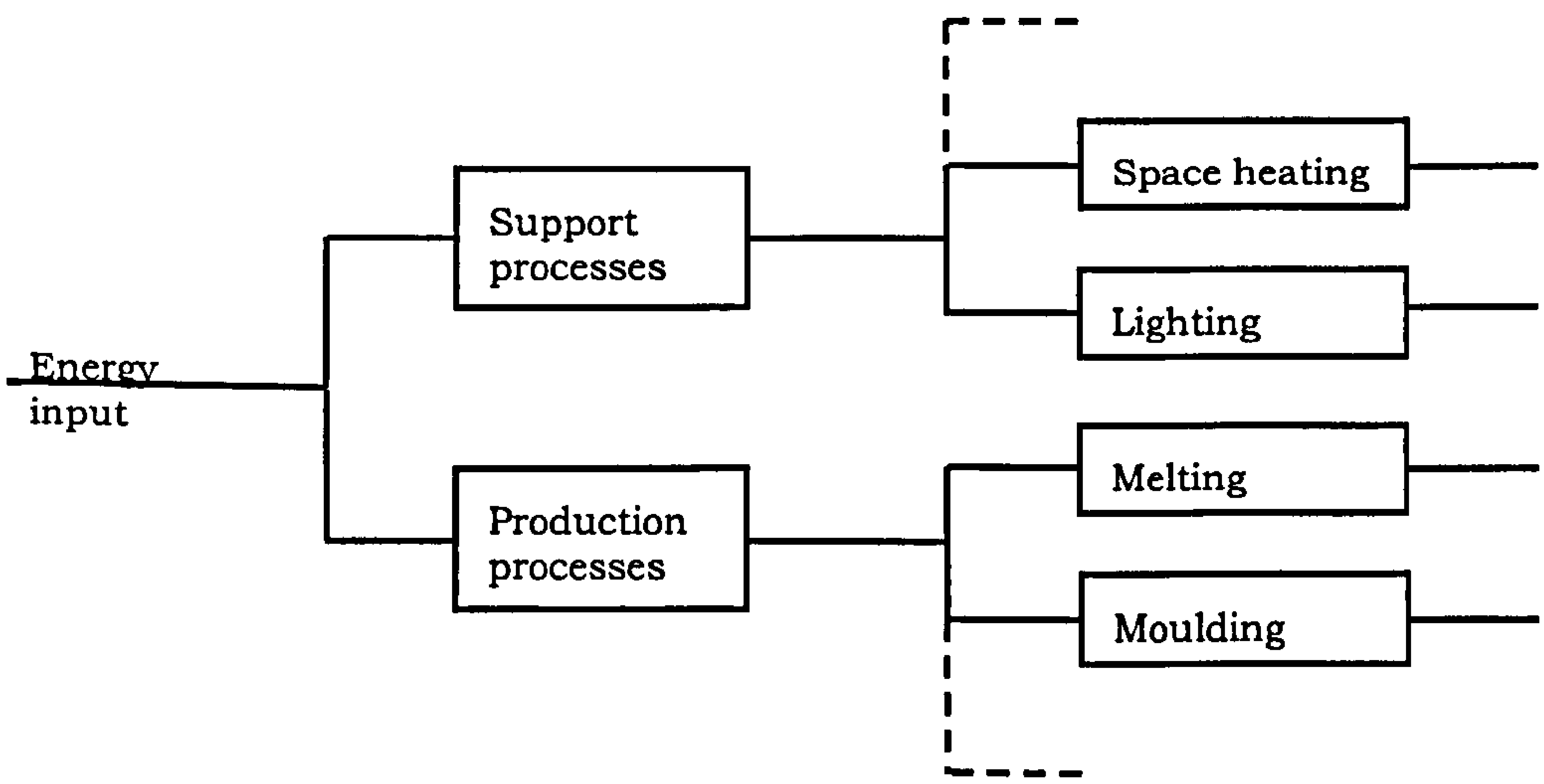


Figure 10.Example of energy flow divided into support and production processes. [Trygg 2006]

3.6 Modelling and simulation of energy systems

3.6.1 Energy system definition

Energy systems is a broad term and must be further defined before it can be used in a context. Energy systems can be many things including, but not limited to: the supply and use of energy within a factory, the Swedish, Nordic, European or global electricity supply system, the heat supply system of a building, or the global energy system. Within these examples there may also be a number of variants depending on how the system is viewed, where the system boundaries are, and which parameters are analysed. Problems can also occur when systems interact with each other. Ingelstam [2002] describes the problems when mixing energy and environmental aspects. With environmental aspects he means CO_2 emissions. He points out that energy supply and use occurs regionally while CO_2 emissions will affect the globe approximately uniformly no matter where the discharge is.

Most energy systems described in different contexts are constantly changing. New sources of energy appear and energy from renewable sources, such as solar, wind and wave energy is increasing, changing the energy supply systems. Regional supply systems change when new buildings and factories are built. The efficiency of cars and industrial equipment has improved while the demand for these is at the same time varying constantly. Examples such as these show the need for accurate calculations and the need to adapt to new technologies such as energy modelling, simulation and analysis of the systems.

3.6.2 Energy models

There are advantages to using models to answer questions about a system, real or constructed, where practical experiments are difficult or impossible to conduct. Several models for analysing energy systems have been developed. A review of different types of energy models has been presented by Jebaraj and Iniyan [2006]. This review divides energy models into categories:

- Energy planning models

- Energy supply-demand models
- Forecasting models
- Optimisation models
- Energy models based on neural networks
- Emission reduction models

Another review presented by Hiremath et al. [2007] divides energy models into other, somewhat similar, categories:

- Optimisation models
- Decentralized energy models
- Energy supply/demand driven models
- Energy and environmental planning models
- Resource energy planning models
- Energy models based on neural networks

The way in which these categorisations are made shows that there is no single way to categorise energy models and that all models are not covered by these categories. Some categories overlap between the presentations and some modelling techniques in the studies can fit more than one category. The usage of different models also varies, from visualisation to deeper analysis and simulation. The definition of a system varies within and between categories and naturally also its components, connections, boundaries and surroundings, which form the system definition. The research described in this thesis does not use any of these described models but instead tries to complement the set of models with a type of model that simulates discrete production.

Among planning and forecasting models there are interesting approaches for making plans and forecasts of energy use within short and long time periods. However, most of them are for households, regions, nations and buildings. Only in optimisation modelling is industry frequently represented. One example is the use of the MIND (Method for analysis of INDustrial energy systems) method [Karlsson and Söderström 2002] for optimising industrial energy use. Technical solutions for these types of optimising models are often Linear Programming (LP), Mixed Integer Linear Programming (MILP) or Multi-Objective Fuzzy Linear Programming (MOFLP). These models have the disadvantage that small time steps are difficult to use and due to the nature of the algorithms, the computer calculation time would be too long. The result from running one of these models can be an optimal solution. Variations over time or the behaviour of the system close to the optimal solution are not shown.

Optimisation models, such as MIND, can also be used together with other analysis methods such as pinch analysis and exergy analysis, both described as process integration methods. Both these are based on thermodynamic principles. Pinch analysis has many applications, such as optimising heat exchanger networks and determining minimum heating and cooling demands for a process. Bengtsson et al. [2002] describes a study at a pulp and paper mill where the aim was to evaluate different alternatives, taking into account economic, technical and practicable constraints. Exergy analysis is about analysing the quantity and quality of energy or the "thermodynamic potential" [Wall and Gong 2001]. Gong and Karlsson [2004] used exergy analysis in a pulp and board mill to show the most inefficient processes. The MIND method was then used to study different investment alternatives.

3.6.3 Energy simulation

Simulation within the field of energy is closely related to energy modelling. To be able to make a simulation, a model is needed, but not all models are used for simulation. Most of the applications are about simulating the flow of energy carriers such as air and water in systems or buildings [Rohdin and Moshfegh 2007] [Zhu 2006].

Simulation of Energy Management Systems (EMS) is described by Brady [2001, 2002] in two articles where a simulation model is used to examine the requirements of a steel mill in a constrained electricity supply environment. The simulation model is used to analyse policies that quantify the costs and benefits of strategies that are efficient for both user and supplier, where the user will be given credits for making a decision that is best for the entire energy system.

Simulation of production is described by Mori et al [2004]. They describe a simulation-based scheduling system with the aim of optimising several objectives such as minimising energy use, makespan and tardiness. The model has a fixed, limited number of product types, process operations, equipment and tools. A simulation model is used and optimised using Immune Algorithms (IA).

Simulation models can also be used for thermodynamic analysis such as pinch analysis. Fritzson and Berntsson [2006] describe a simulator where heat exchangers, compressors etc. are represented, temperatures and efficiency for the blocks defined and simulations conducted to find the optimal use of the system.

3.7 Means of control

Every company is part of a regional, domestic, European and global energy system. These systems need to be balanced and there are several laws and agreements to be considered. To be able to keep the agreements, reduce pollution and/or reward energy efficiency efforts, Sweden has for a long time used economic means of control within the energy area. Taxes and supported investments are traditionally the most common means of control. Due to the introduction of the EU ETS and ECS, Sweden has turned more to market based means of control. These means of control can be divided into three different categories: *taxes*, *subsidies* and *market based means of control* [SEA 2006a].

- **Taxes,** which are the traditional means of control, are today used on fuel, electricity and heat in the form of gas taxes, CO_2 taxes and electricity tax.
- **Subsidies** are different focused contributions such as:
    - Investment support to stimulate the development of new technologies.
    - Conversion aid to convert from oil and electricity to renewable alternatives.

- **Market based means of control** are based on fixed rules, drawn up by for example the government, and where the actors in the market decide how to reach the goals.
    - EU ETS is an economic mean of control with the aim of reducing the discharge of green house gases. The first part of the trading scheme is divided into two periods: 2005-2007 and 2008-2012.
    - ECS, which is a technical mean of control that gives the electricity producers certificates for every MWh produced from renewable energy sources.
    - PFE, which is stimulating energy intensive industry to focus on energy efficiency work by reduced taxes.

All the above mentioned means of control have been introduced to reduce energy use and greenhouse gases in the atmosphere. They have different impacts on different companies and companies have different abilities to control their costs. The current means of control demand varying degrees of administration within the companies.

3.8 Summary of energy use

Energy use has a great impact on global warming and the best way to mitigate global warming is by energy efficiency. Energy use and energy prices vary between countries, both in a global perspective and between countries in Europe. These variations create difficulties in introducing well functioning means of control. A mix of taxes, subsidies and market based means of control demands that energy-purchasing companies constantly keep themselves updated to be able to reduce energy costs.

The situation in the Swedish electricity market makes it difficult for SMEs, a category to which most Swedish foundries belong, to have an impact on their own prices. Smaller companies therefore also have higher prices. Companies of different sizes also have different drivers for and barriers to energy efficiency work. However, the potential for energy efficiency is substantial in all parts of industry and means such as energy audits and different models for energy efficiency work are used, with the intention of increased energy efficiency. A structured approach to energy management and control is also desirable.

This chapter has described prices, market forces and means of control on global, European, national and industry levels as well as drivers and barriers for efficiency work. All parameters have an impact on how and to what extent energy efficiency work is carried out and have increased the need for tools such as modelling and simulation in industrial production. It has described how energy systems in the past have been modelled and optimised, showing that modelling and simulating energy use within discrete production can contribute to the science base and to the industrial need for fast, accurate tools.

The way energy management, auditing and efficiency work has been and is currently carried out in industry has been important input for the work of establishing a new methodology for working with simulation of energy use. Some of the parameters such as system boundaries and division of processes are defined in the same way as when working with other modelling tools while other parameters differ. Energy related data from audits and measurements have to be treated in a way that makes it possible to handle the information in a simulation model.

4 Simulation

Computer simulation is today being used for various applications. Simulation is still an emerging technology, even though it is already in common use in a wide range of areas including the military, logistics and manufacturing. Simulation is a growing tool also in non-engineering areas such as health care, finance, agriculture and ergonomics.

In this chapter simulation and simulation methods in general will be presented. The discipline of simulation includes a wide range of sub-disciplines. This research, and hence also this chapter, focuses on Discrete Event Simulation (DES) and manufacturing applications for DES.

4.1 Computer simulation

The word simulation can refer to different things depending on the situation and the aim of the simulation. Several researchers have tried to make a truthful definition of simulation. One of these definitions is presented by Pegden et al. [1995]:

> *We will define simulation as the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and/or evaluating various strategies for the operation of the system.*

Some shorter and more concise definitions have also been put forward, such as one by Robinson [1994]:

> *A simulation is a model that mimics reality.*

No matter what definition is used to describe simulation there are some things that are common to most of them. One is the fact that a system is imitated to generate a better understanding of it and to find answers to questions about the system. A common label for simulation is decision support tool [Page 1994].

Simulation, in a wide perspective, can be classified in different dimensions and with different potential for analysis. The type of model used is dependent on the type of system and the purpose of the study. Figure 11 shows some of the model types and their distinctions. Without going into detail on every type of simulation, the models considered in this research study, discrete event models for computer simulation, are mainly numerical, abstract, stochastic, dynamic, discrete, autonomous and descriptive. Some discrepancies may appear such as the appearance of deterministic parts and also continuous parts in a model.

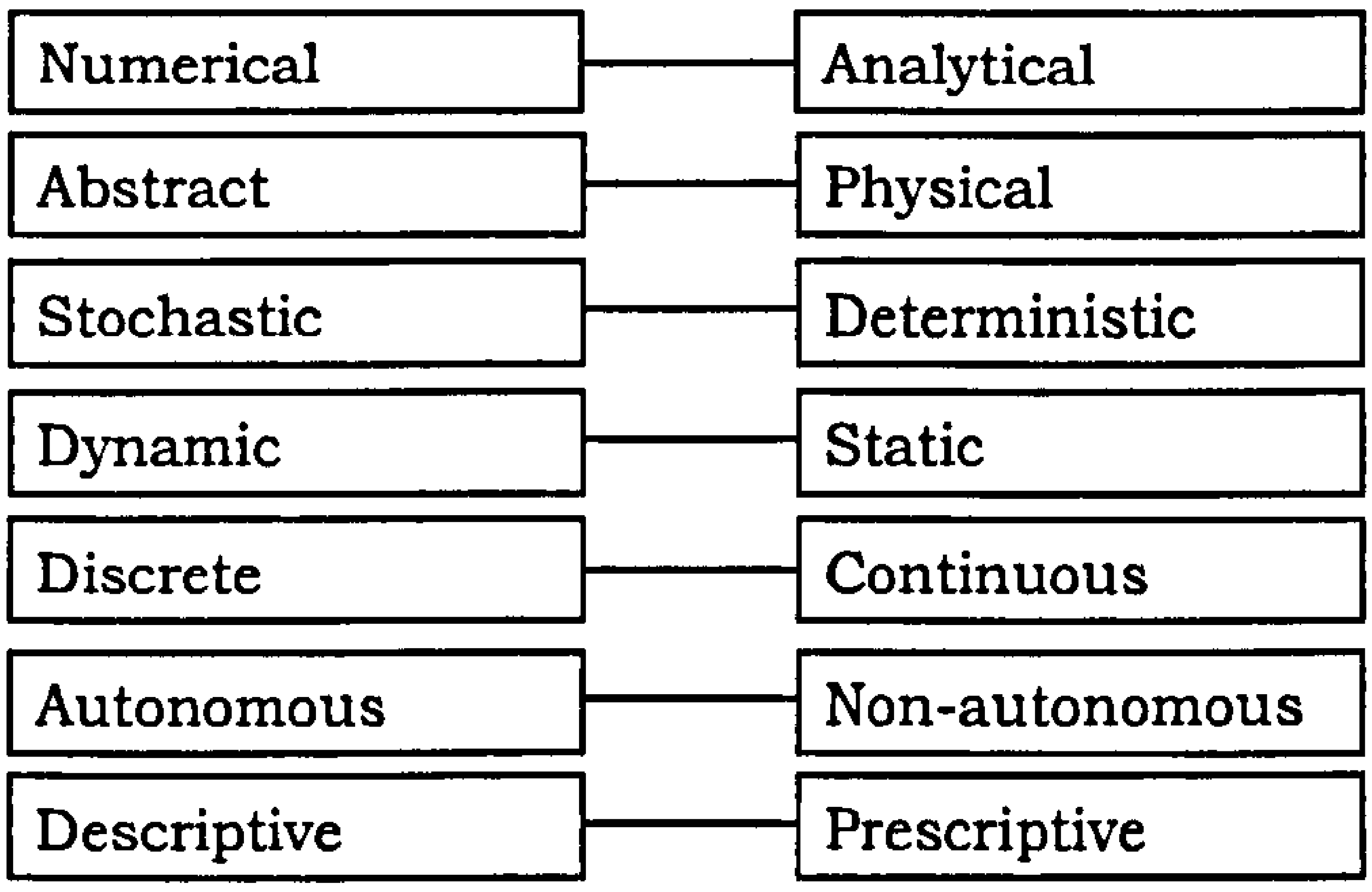


Figure 11.Classification of model types. [Banks et al. 2005] [Robinson 1994] [Law 2007] [Kelton et al. 2004]

Nothing in the definitions indicates that simulations can not be performed manually, but with the vast amount of time it would take to make all calculations manually most simulations are performed with the help of computers. The speed of modern computers has greatly decreased the number of applications where technology is not good enough to perform simulations. However, for DES, a few guidelines exist as to when simulation should not be used, for example *when the problem can be solved analytically*, *when time or data is not available*, *when system behaviour is too complex or can not be defined* or *when it is easier to perform direct experiments* [Banks et al. 2005].

More importantly, there are many areas where simulation can be used. In these circumstances there are several advantages to using simulation. Pegden et al. [1995] lists some advantages:

- New policies, operating procedures, decision rules, organisational structures, information flows etc. can be explored without disrupting ongoing operations.

- Hypothesis about how and why certain phenomena occur can be tested for feasibility.

- Insight can be gained about which variables are most important to performance and how these variables interact.

- A simulation study can prove invaluable to understanding how the system really operates as opposed to how everyone thinks it operates.

- Simulation's great strength lies in its ability to let us explore "what if" questions.

Even though there are several advantages there are also some drawbacks to using simulation: [Pegden et al. 1995]

- Model building requires specialised training.

- Simulation results are sometimes difficult to interpret.

- Simulation analysis can be time-consuming and expensive.

"Simulation is an art and science" says Shannon [1998] meaning that conducting a simulation study is a problematic issue. She also says that the science part, understanding the theory behind simulation, can be taught but that the art part, knowing how to build a simulation model of a system efficiently, must be learned by experience. But no matter how good you are at modelling it is impossible to build an exact replica of a system. Law [2007] states:

> *A simulation model of a complex system can only be an approximation to the actual system, no matter how much effort is spent on model building. There is no such thing as absolute model validity, nor is it even desired. The more time (and hence money) that is spent on model development, the more valid the model should be in general. However, the most valid model is not necessarily the most cost-effective.*

Similarly Pegden [1995] states:

Since all models contain both simplifications and abstractions of the referent, real-world system, no model can ever be absolutely correct, i.e., it can never have a one-to-one correspondence with its real-world counterpart.

4.2 Discrete Event Simulation

Among the many simulation techniques available, Discrete Event Simulation (DES) can be said to be one of those used for most purposes, proven by the large number of cases carried out in different areas. DES provides a tool for analysis of complex systems that are dynamic in nature and that spread over different levels or departments within an organisation or even between different organisations. DES can help in verifying decisions on investments, shortening ramp-up times, increasing utilisation and enhancing productivity. It can also be a suitable tool for educational purposes.

The technique of DES is very suitable for the manufacturing industry. Harrington and Tumay [2000] describe DES thus: "In this type of simulation, the state of the model changes only at discrete (possibly random set of points) event times." In practice, the central part of a simulation model is the queue in which all these events are stored. These events are executed chronologically and the events can in turn create new events that are put in the queue. This is also the way many industrial production facilities can be represented, as a discrete set of events occurring after each other, being dependent on the preceding events and the current status of the system.

There is a long tradition of using the technique of DES; its history goes back to the 1960s. The first Winter Simulation Conference (WSC) [WSC], which is the most well-known DES conference, dates as far back as 1967. In the beginning there was no animation and the computer had less power than today but it is still the same type of questions that are addressed today when considering DES for manufacturing industry.

4.3 Simulation method

No matter what process of engineering is performed, there is a need for a structured approach to be able to produce the most useable and reusable solution. Over the years several simulation methods have been presented. A method in its most simple form is presented by Fishwick [1995] explaining the three primary processes of simulation: *model design, model execution* and *execution analysis.* In practice, a more detailed method is needed and several advanced simulation methods are described in literature [Banks et al. 2005] [Jägstam 2003] [Law 2007] [Musselman 1994] [Pegden et al. 1995] [Pidd 2004] [Robinson 1994] [Watkins 1993]. One which is widely accepted within the simulation community is described by Banks et al. [2005]. The method describes 12 activities in a simulation project, see Figure 12. These activities are described in greater depth in sections 4.3.1 - 4.3.9.

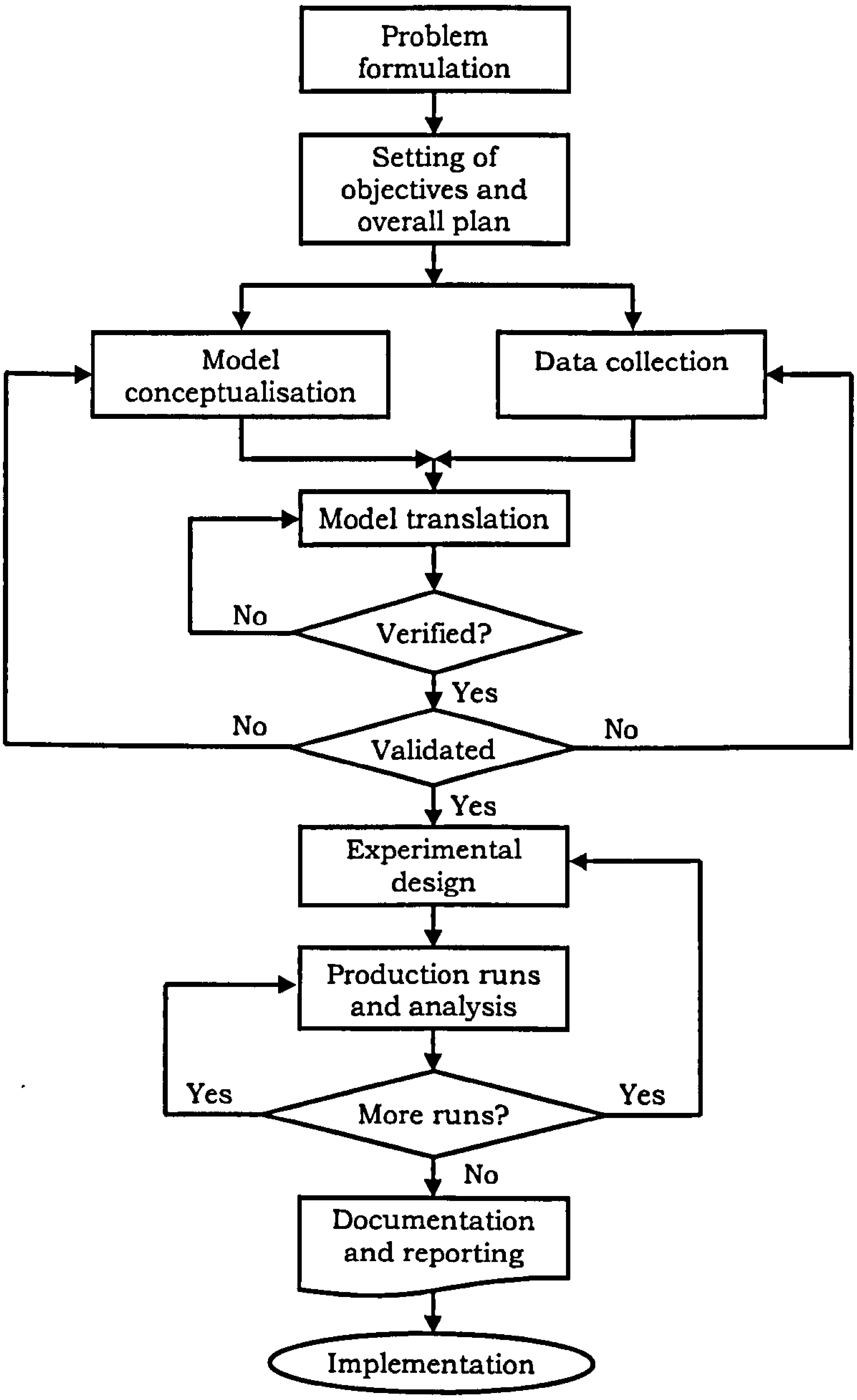


Figure 12.Steps in a simulation study. [Banks et al. 2005]

4.3.1 Problem formulation and setting of objective

A simulation study should always begin with a problem statement. The problem statement must be clear and understood by the client as well as the simulation expert. All assumptions made about the system must be accepted by the client. The problem formulation may, even with previously mentioned precautions, change during the progression of the simulation project [Banks et al. 2005].

The objectives of the simulation study are the questions that the study is supposed to answer. If different scenarios are to be simulated and investigated these are set at this stage. At this stage the requirements for carrying out the simulation study are set, such as cost and time frames, software and hardware issues, and expected outcomes from different stages of the study [Banks et al. 2005].

4.3.2 Model conceptualisation

From the system of interest an abstraction is made, the conceptual model. This contains a series of logical relationships that comprise the system, its building blocks and its behaviour. At this stage the data needed to support the simulation model is defined. Ideally the researcher can begin to collect not already available data as soon as possible to get a statistically justified amount of data.

One approach at this stage is to begin modelling at a higher level and increase the complexity until the appropriate level of complexity is reached, starting with the main features such as machines and queues, then adding material handling and operators and finally special features. There is a great need for client involvement at this stage so that the model does not grow too large. Often there are features that greatly add to the cost of the simulation project, while adding little or nothing to the quality of the output.

Robinson [2006] states that conceptual modelling is probably the most important aspect in the process of developing and using simulation. Robinson mentions different approaches and levels of importance in different authors' views of conceptual modelling and he then stresses the need for agreement on a definition of conceptual modelling among simulation analysts and the need for more validation connected to conceptual modelling.

4.3.3 Data collection

It has been argued that the data collection process is one of the most crucial stages in the model building process [Kelton 1997] [Perera and Liyanage 2000]. It tends to be very time-consuming and difficult. It can be a matter of getting too little data, too much data or just the wrong data [Sadowski and Grabau 2000].

The quality of the input data is crucial to the output from the simulation model. The type of data is also important. Most systems involve some kind of uncertainty; the simulation model should therefore also do so. Using only fixed deterministic data causes the simulation model to lose some of its strength. Kelton [1997] reasons around this while developing the well-known term GIGO (garbage in, garbage out) also into DIDO (deterministic in, deterministic out) and RIRO (random in, random out) to again stress the importance of the quality of input data.

Perera and Liyanage [2000] present seven major pitfalls when collecting data and the ranking of these. These are presented in order of impact in Table 1.

Table 1. Ranking of the impact of the major pitfalls in data collection. [Perera and Liyanage 2001]

Major reason	**Rank**
Poor data availability	1
High level model details	2
Difficulty in identifying available data sources	3
Complexity of the system under investigation	4
Lack of clear objectives	5
Limited facilities in simulation software to organise and manipulate input data	6
Wrong problem definition	7

Robertson and Perera [2002] also present four methods of data collection for model building, see Figure 13. The different methods range from only manual input of data for the simulation model to fully automated systems for transferring data into, and updating data in, the simulation model. Managing data is also considered to be one of the key issues in the enhancement of simulation software [Jain 1999] and in the development and wider usage of simulation [McLean and Leong 2001].

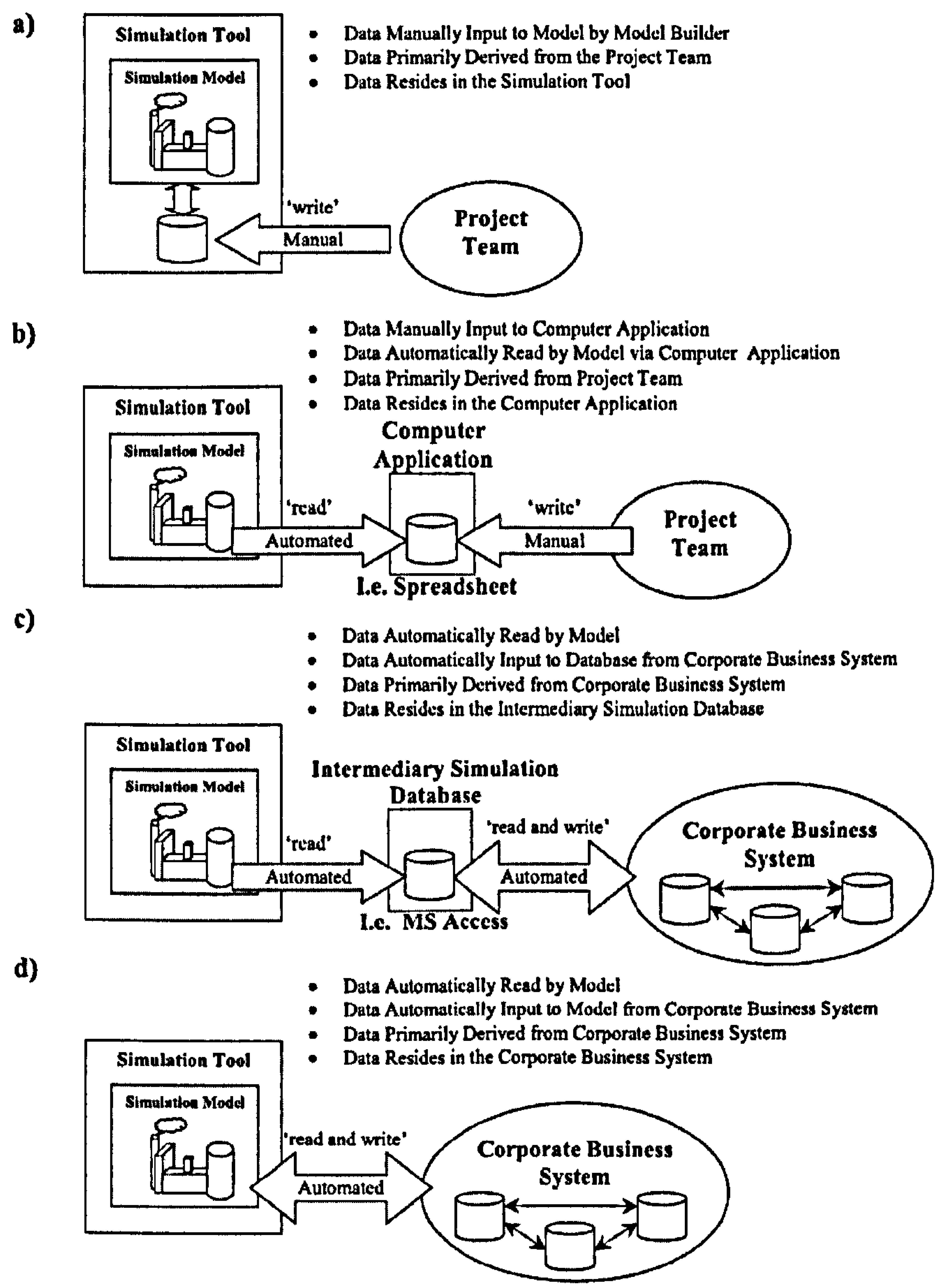


Figure 13.Data collection methods for model building. [Robertson and Perera 2002]

Commercial simulation packages often include modules for displaying, analysing and summarising input data. However, not all packages include these modules and in those cases there are other commercial specialised tools that can be used such as ExpertFit [2007] and Stat::Fit [2007].

4.3.4 Model translation

In the model translation phase the conceptual model constructed in the earlier stages is translated into a simulation model that is recognisable to, and possible to run on, a computer. Most simulation engineers today use Commercial-Off-The-Shelf (COTS) simulation packages. Model translation is probably the most time-consuming stage in the simulation process. Umeda and Jones [1997] mention a range between 30 and 60% of the total project time and Trybula [1994] argues for somewhere between 10 and 40%. The outcome of model translation is highly dependent on the work done in the previous steps and it is important to build a model that represents the system in a good way and at the right level of abstraction, as determined in the previous steps.

4.3.5 Verification and validation

The verification of a model should answer the question of whether the model behaves in the right way. The verification process should be an ongoing process during the study. It is also good to use available debugging tools and other help tools during the process to further enhance the verification process [Banks 2000] [Kleijnen and van Groenendaal 1992] [Law 2007] [Sargent 2004] [Shannon 1998].

The validation of a model should answer the question of whether the model is an accurate representation of the simulated system. If the simulation model is a representation of an actual system, the question is whether it can be substituted for that system and used for experimentation. [Banks 2000] [Kleijnen and van Groenendaal 1992] [Law 2007] [Sargent 2004] [Shannon 1998].

Validation can be conducted in different ways and by different people: according to Sargent [2004] a model can be validated by *the simulation team itself*, *the user of the model*, *a third, independent, party (also called "independent verification and validation", (IV&V))* or *using a scoring model (where scores are determined subjectively when different phases of the validation process are gone through)*. Sargent [2004] does not think that using the scoring model is a good approach and he believes that the IV&V approach should be used concurrently with the validation done by the modelling team itself and the model user. Sargent [2004] also specifies several different techniques and tests that can be used to conduct validation and verification of a simulation model of which some are:

- Using *animation*, where the behaviour of the system on the screen is compared to reality.
- Using *degenerate test*, where the degeneracy of the model is tested by selecting values of different input parameters.
- Using *extreme condition test*, where extreme and unlikely combinations of factors are tested.
- Using *historical data*. Law [2007] calls this approach the "correlated inspection approach". With this approach, historical data is fed to the model and the output is compared with the output from the actual system (See Figure 14).
- Using a *sensitivity analysis* to investigate whether a change in the input data corresponds to an expected change in the output of the model.
- Using the *Turing test*, where individuals who are familiar with the system are asked if they can discriminate between system and model outputs.

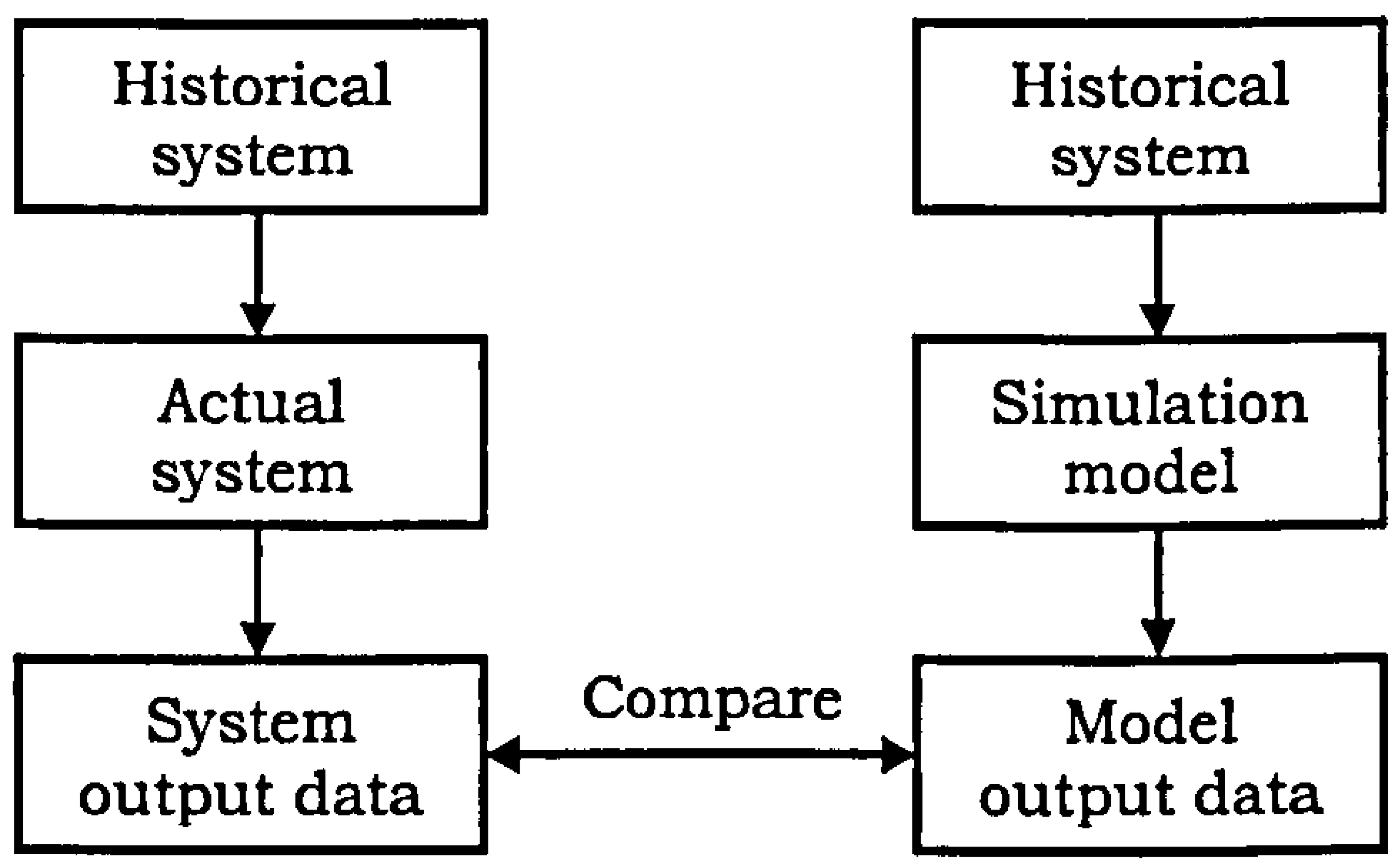


Figure 14.The correlated inspection approach. [Law 2007]

Often, several of the methods above are used to validate and verify a simulation model. During the process, one should be aware of the differences between verification and validation where verification is used to check that the model is correctly built, based on the conceptual model, and validation is a means of checking that the right model is built, a model that is an accurate representation of the actual system.

4.3.6 Experimental design

At the experimental stage data is fed to the model and a series of predefined experiments are conducted. These experimental data are varied with the aim of studying the performance and behaviour of the model, see Figure 15.

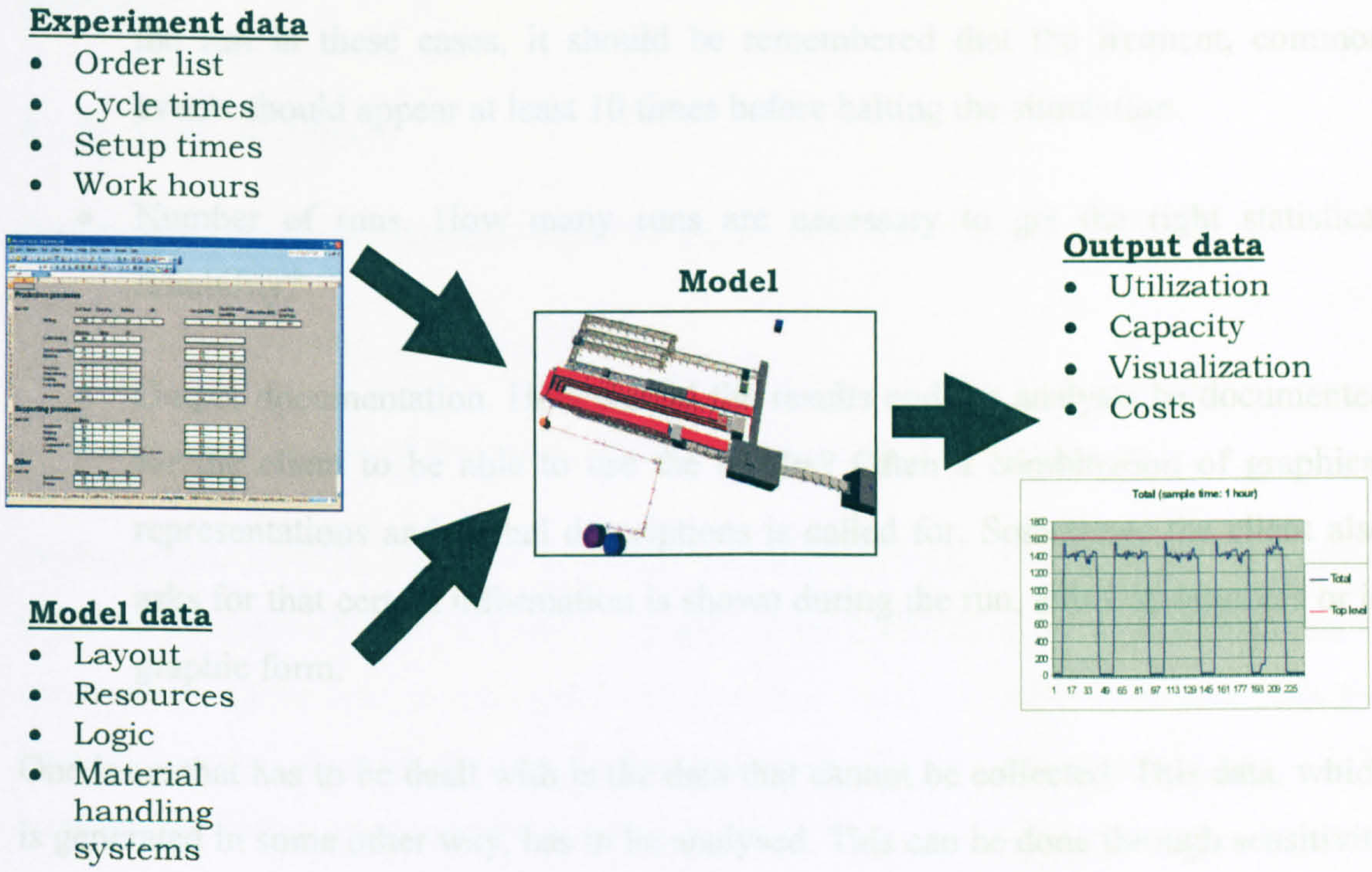


Figure 15.A simulation model is fed with experimental data during simulation and delivers output data.

The experimental stage should be prepared for in the early phases of a simulation study, problem formulation and setting of objectives. The experimental design should focus on answering the initial objectives of the simulation run. Decisions have to be made concerning several issues, for example: [Banks 1998] [Kelton 2000]

- Initialization and start-up criteria. What is the correct state to start the experiment from? Can the model be fed with data so that experiments can start from the beginning or does a “steady state” have to be reached? How to handle randomness, such as different random seeds, has to be decided.

- Length of runs. For how long does the simulation model have to run to give useful results? It can for example be when a shift, day or week has ended or after a particular number of parts have been produced. Sadowski [1993] calls this type of system with a defined start time and a defined time for operations a *terminating system*. Sometimes the system does not have a defined start time or time for operations; the point of interest is then instead to watch the simulation during its equilibrium [Kleijnen and van Groenendaal 1992]. Sadowski [1993] calls this type of system a *non terminating system*. When deciding the length of the run in these cases, it should be remembered that the frequent, common events should appear at least 10 times before halting the simulation.

- Number of runs. How many runs are necessary to get the right statistical reliability?

- Output documentation. How should the results and the analysis be documented for the client to be able to use the results? Often a combination of graphical representations and verbal descriptions is called for. Sometimes the client also asks for that certain information is shown during the run, either as numbers or in graphic form.

One issue that has to be dealt with is the data that cannot be collected. This data, which is generated in some other way, has to be analysed. This can be done through sensitivity tests [Law 2003].

The experimental stage can be a time-consuming stage. Sometimes additions need to be made to the model at this stage to be able to feed the model the right set of data and to capture the right output data for analysis. The client will also often make additional requests at this stage due to situations having changed while going through the earlier phases.

4.3.7 Production runs and analysis

At this stage the experiments that were defined earlier are run and the performance of the model is analysed. Statistical methods are used to see if the results are reasonable.

Using the visualisation capabilities of the simulation tools may help in drawing conclusions about the system's behaviour.

If the results here are not satisfactory, either by not being accurate or detailed enough or by not fulfilling the objectives, alterations may have to be made. Note that this is not the same thing as the client not getting the result they hoped for. A loop back to all previous levels can be made to make sure that the right question is answered, that the right results and the right amount of results are produced, and that an accurate analysis can be performed.

4.3.8 Documentation

Documentation of a simulation project should include: [Banks et al. 2005]

- Documentation of the model itself
- Documentation of the system behaviour, results and analysis.

Documentation of the model is necessary to be able to use and reuse the simulation model in the most efficient way and to be able to make alterations to it. It is important to know what data is used in the model and how it is used, and what simplifications and assumptions are made in the model. Knowing how the simulation model works will increase confidence in the model [Nordgren 1995].

The scope of documentation of system behaviour, results and analysis differs greatly between projects. Already at the problem formulation stage, it should be decided how the project should be documented. The level of detail in the documentation will proportionally increase or decrease the amount of documents needed. Proper, structured documentation also helps keep the documentation to a minimum [Banks et al. 2005] [Jägstam 2004].

4.3.9 Implementation

If successful, the results from the simulation project are implemented at this stage. The implementation can vary from a few justifications, for example on a machine or a work description, to constructing a whole new manufacturing line or factory. The success of the simulation project often comes down to whether the simulation engineer has followed all the steps and also whether the client has been actively involved in all the steps.

4.4 DES programs

Discrete Event Simulation (DES) programs possess great power and flexibility and are continuously becoming more and more powerful. However, improved programs with increased functionality are also more complex, which does not always make them easy to use. It is difficult to achieve both ease of use and a wide range of applications within the programs. [Kuiper 1998] [Shewchuk and Chang 1991] [Swain 1999]

When selecting simulation software it is important to make the right choice. If the "wrong" software is chosen, the time required to complete the project might be greatly increased or even make it impossible to complete. When choosing a program, Robinson [1994] states there are two questions that need to be evaluated:

- Which type of package most suits the organisation and its structure?
- Which specific package best fits the applications to be modelled?

He further splits this into six stages [Robinson 1994]:

1. Simulation language versus simulators.
2. Select criteria for basis of decision.
3. Determine relative importance of each criteria.
4. Investigate software available.
5. Information gathering.
6. Select the software.

Several overviews, evaluations and surveys of programs have been made to support the decision on the choice of simulation program [Boer et al. 2006] [Hlupic 2000] [Johansson et al. 2002] [Klingstam and Gullander 1999] [OR/MS Survey 2005] [Swain

1997] [Swain 1999]. Different approaches have been used and different aspects have been analysed. For example Johansson et al. [2002] describe an evaluation of DES software for Dynamic Rough-Cut Analysis (DRCA). DRCA means building models rapidly and efficiently. Four different software packages are evaluated using Simple Multi-Attribute Rating Technique (SMART) on a reference model built in these four DES software packages. The study shows that some software packages are more suitable for DRCA than others and that some programs are cheaper and easier to use but often lack possibilities for building complex models when needed. In another example, in OR/MS Today [OR/MS Survey 2005], an extensive study of most simulation programs on the market was presented. This study was of a more technical nature and presented the programs and vendors as well as some technical aspects and general modelling capabilities.

Not only are the more advanced programs evaluated. Stanford and Graham [1998] question whether managers and non-technical consultants are ready for low-cost, and hence less advanced, DES programs. This study is based on interviews and shows diverse knowledge, interest and possible use of these types of programs.

4.5 Applications of DES

In a report from The Integrated Manufacturing Technology Roadmapping Project (IMTR) [IMTR 2000], formed by the Integrated Manufacturing Technology Initiative (IMTI) [IMTI 2000], it is said about Modelling and Simulation (M&S) that:

> *...no other technology offers more potential than M&S for improving products, perfecting processes, reducing design-to-manufacturing cycle time, and reducing product realisation cost.*

Considering that the IMTI was put together to look at all manufacturing areas, this is quite a strong statement, even though it includes modelling and simulation in general, not merely DES.

Even though there is this great potential there are few companies that have been able to integrate the technologies into their businesses. Williams [1996] says that achieving the ongoing, long-term benefits using simulation by making simulation a "corporate norm" is rare. Barriers to achieving this are not only technological issues but also difficulties in integrating new working methods into the well established ones. To overcome these barriers, companies have to put greater effort into the organisational aspect of integrating simulation in their work methods [Jägstam 2004] [Klingstam 2001].

4.6 Use of DES in industry

Even though few companies, as mentioned above, use simulation as an integrated part of their manufacturing system successful projects are being carried out around the world all the time. Some of the main areas of research and applications within DES are manufacturing, health care, business process re-engineering, transportation, food processing, construction and the military [Banks et al. 2005] [Pidd 2004]. But there are several more areas where DES is used and applications are presented every year at the Winter Simulation Conference [WSC].

To what extent DES is used in industry is not easy to define. One study conducted by Jackson [1998] shows that, in Sweden, 31 percent of companies with more than 50 employees use DES. Many companies in this study started to use DES as soon as they became aware of the tool's existence. Not many companies decided not to use DES once they found out that the tool exists. Another survey, conducted by Eriksson [2005], showed that 4 to 7 percent of Swedish companies use DES. 4 percent use DES frequently and up to 7 percent use DES to some extent. These surveys show that there is a difference in usage depending on how the questions are asked and in what country the survey is conducted, even though Sweden and Germany have a similar industrial tradition. In addition to these studies, a study by Umeda and Jones [1997] shows that the use of simulation in Japanese industry is modest compared to the United States but they also mean that it is on the rise due to the increased focus on virtual manufacturing and integration. This is confirmed by Holst et al. [2000] who state that simulation is not yet an integrated part of Japanese development system. Holst et al. consider this to be because the acceptance of simulation is low and that the full potential of simulation has not been realized.

When simulation is introduced into an organisation, Centeno and Carrillo [2001] say that there tend to be at least four obvious attitudes that appear. The first three have the potential to work in an unfavourable way as regards usage:

- **Total scepticism** – This attitude includes customer comments such as "it will not work since the procedures we use are too complex" and "we are doing fine the way it is".
- **Magical excitement** – It is very risky if managers believe that simulation can "cure all" and that the model will be able to represent any and all areas of the company. Even though this attitude is a "gold mine" it can turn the opposite way if a study does not deliver to the high expectations.
- **Uncommitted support** – With this attitude the company shows that the need is understood but neither time nor resources are available.
- **Supportive** – If this attitude is shown it merely needs to be "nurtured".

Since there are often obstacles to overcome before introducing simulation into an organisation, researchers have discussed strategies for increasing the success of implementation. Williams [1996] describes how to make simulation a "corporate norm" by describing appropriate ways to introduce simulation projects, how to increase awareness, how to select software and other aspects where it is more about *how* than *what.*

4.7 Use of simulation in the foundry industry

4.7.1 Simulation tools in the foundry industry

The foundry industry is a very diverse industry. Many companies are SMEs with relatively little knowledge regarding information technology while other companies have come a long way in integrating computer aids in design, product development and production. 3D Computer Aided Design (CAD) tools are nowadays available in most companies. Simulation tools, however, are still quite expensive and therefore less used even though there are simulation programs available today in many different areas. The most widely used are different types of casting simulations. With casting simulations, analyses can be made about for example [Svensson 2001]:

- Mould filling
- Solidification
- Shrinkage
- Deformation and stress
- Temperature and life length of tools

Methods used for these types of simulation are mainly Computational Fluid Dynamics (CFD), Finite Element Method (FEM) and Finite Difference Method (FDM) [Svensson 2001].

These casting simulations have a great impact on new design of both the products itself and the mould. The cores, the placement of ingates, and other design parameters can also be tested with simulation. Using this type of simulation there is a greater chance of reducing porosity, cold shuts and other defects that may occur during the process.

The manufacturing group of simulation tools, including for example DES, Computer Aided Robotics (CAR), ergonomic simulation and assembly simulation is less used and in this group CAR is the most common in the foundry industry today.

4.7.2 Use of DES in the foundry industry

In many aspects Swedish industry is well developed, compared to many other industrialised countries' industry, considering the level of automation, use of IT-tools, ergonomics etc. However, the foundry industry as a subgroup has a highly varying level of development. The size of the companies varies from less than five to several hundred employees. This means that it is difficult for many smaller companies to keep up with the larger ones in, for example, the use of IT tools. In a survey conducted by Rohdin and Thollander [2006b] only 29 percent of the companies were using or had used DES. Of these 29 percent, the majority were larger companies. One of the reasons is that it is not always considered cost effective to invest in simulation programs. Simulation programs have historically been fairly expensive and using the programs demands a competence that is scarce in these companies. The benefits are also often difficult to calculate in economic terms. The most common way to use DES is instead to use consultants to build and maintain models and to use run time licenses for analysis. Swerea SWECAST has conducted roughly 40 simulation projects at almost 30 companies since 1996. Swerea SWECAST is one of the major suppliers of simulation modelling to the Swedish foundry industry but there are also other consultants and some foundries have a DES program of their own. However, even though usage is low there is an interest in the benefits of simulation according to a study conducted by Rohdin and Thollander [2006b].

4.8 Use of DES in production planning and scheduling

Production planning is a diverse area of knowledge. There are many different opinions about different approaches and the research applications are numerous. There is also a vast amount of software available that can help companies with their production planning and scheduling, both COTS software and software produced in-house and hybrid variants such as the use of DES.

4.8.1 Levels of production planning

Planning and scheduling is a continuous process in manufacturing. In literature, these planning activities are generally categorised into three main levels – *strategic*, *tactical* and *operational* (see Figure 16) [Das et al. 2000] [Dewhurst et al. 2001] [Landeghem and Vanmaele 2002]:

- **Strategic planning** – Strategic planning is carried out with the aim of investigating different scenarios such as varying product mixes, analysing a new layout of a planned or existing manufacturing plant or analysing the impact of resource investments. At this level different scenarios are tested and economic calculations are made, leading to a better information base for decision makers. Strategic planning leads to substantial impact on the manufacturing system.

- **Tactical planning** – The main aim of tactical planning is to increase the productivity in the manufacturing plant. The product mix is decided and rough resource planning is carried out. Tactical planning leads to minor changes to the manufacturing system compared to strategic planning.

- **Operational planning** – Operational planning deals with real time or close to real time planning performed every day or several times each day. Operational planning is performed based on information from the tactical and strategic levels and from the current situation in the manufacturing system. Disruptions such as prioritised orders, absenteeism, material shortage and breakdowns often cause the planner to reschedule.

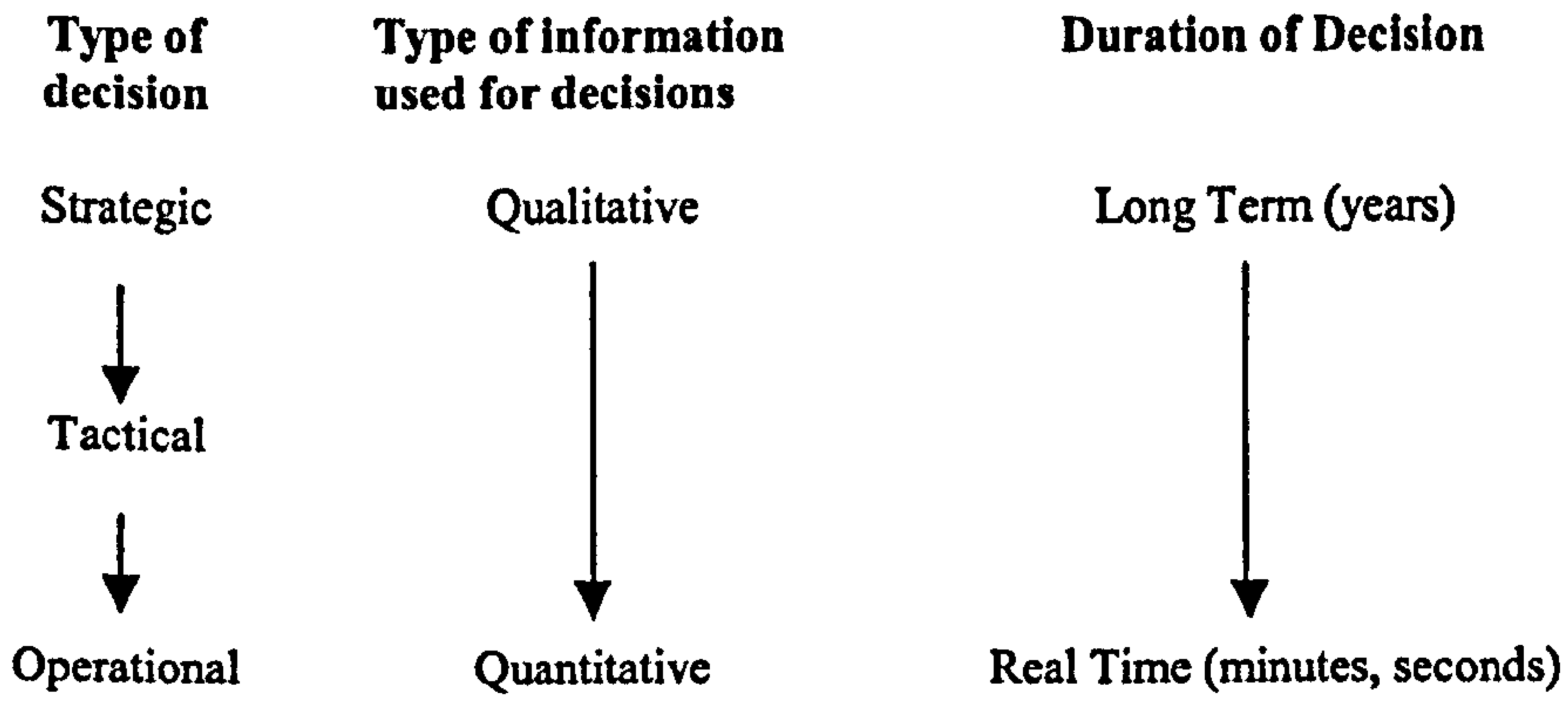


Figure 16.Planning levels in a manufacturing company. [Dewhurst et al. 2001]

These different planning levels are closely related to the business organisation. Tactical planning creates a link between sales, marketing, distribution, suppliers and the manufacturing operations [Das et al. 2000]. Operational planning is linked to the shop floor operations with last minute plans and updates. Strategic planning is closely related to the management and to the overall ambition of the company.

4.8.2 Scheduling rules

Scheduling is concerned with sequencing orders that have been released for production by deciding when, where and how these orders should be manufactured.

Most scheduling is performed with the help of different heuristic rules such as Earliest Due Date (EDD) rule, Cost Over Time (COVERT) rule, Shortest Processing Time (SPT) rule, Critical Ratio (CR) rule and many more [Sule 1997]. There are differences between these rules and the algorithms are also dependent on whether the company produces to customer order or to stock. Hybrid variants also exist.

4.8.3 Discrete Event Simulation in planning and scheduling

In their papers from the 1999 Winter Simulation Conference, about the future of simulation, Davis [1999] and Jain [1999] say that simulation based scheduling is not entirely a new area but at the same time far from fully explored. However, DES is today a well developed tool for evaluating manufacturing facilities. Development has gone from being a tool for strategic decision support purposes mainly into being used for planning and scheduling at tactical and operational levels as well. It is essential that a new scheduling method is usable and profitable. Simulation supported scheduling is argued to be, and has proved to be, a usable method [Appelqvist and Lehtonen 2002] [Chong et al. 2003] [Johtela et al. 1997] [Koh et al. 1996] [Lehtonen et al. 2003] [Mazziotti and Horne 1997] [Musselman et al. 2002] [Randell and Bolmsjö 2001] [Sims 1997].

The reasons for using simulation in planning and scheduling vary. In two papers by Appelqvist and Lehtonen [2002] and Lehtonen et al. [2003] the intention was to increase the help available to the planners when optimising production by means of DES and optimisation algorithms. Randell and Bolmsjö [2001] showed with a proof-of-concept demonstrator a database-driven simulation model with the aim of reducing modelling time. Koh et al. [1996] aimed at using a database-driven simulation for scheduling of a job-shop which increased performance by up to 20 percent. From these examples it is clear that both researchers and companies are starting to use simulation based planning. Some have tried to make the planning fully autonomous but generally some interaction by the planner is needed. Sometimes it is an interactive process between the planner and the system [Johtela et al. 1997].

Simulation models used for operational planning need to be more detailed than models for typical simulation studies [Koh et al. 1996]. The reason is that the result from the simulation is a detailed operation plan which in itself needs to be accurate. Koh et al. [1996] also stress the importance of re-validation when making alterations to such models. To achieve a more accurate model Sims [1997] say that there are a few components that need to be defined to build a simulation model that can be used for planning and scheduling. These are for example: *when people, machines etc. are available*, *what products need to be made* and *when the products need to be made*. Sims also stresses that the most important piece of the model is to define the rules that assign the work to the resources, regardless of how simple or complex they might be.

In complex systems, it is usually hard to calculate the effect of scheduling or planning decisions and the decisions' actual impact on Key Performance Indicators (KPIs) such as cost, throughput, lead-time or profit [Dalal et al. 2003]. By taking these issues into consideration when building a simulation model for manufacturing systems design, the simulation model can also be helpful for these purposes, resulting in direct feedback about how well the results will correlate to the company goals.

The number of simulation models integrated into existing systems such as ERP systems or models using information direct from these systems is growing. This is important since, according to Rizzi and Zamboni [1999], the implementation of an ERP system can be considered to be one of the most effective paths towards traceability. Such an implementation will facilitate integration between modules, data storage/retrieval processes and management and analysis functionalities, combined with the typical functionalities of stand-alone applications. Even though implementing ERP systems must be seen only as a preliminary step towards internal process efficiency improvement [Rizzi and Zamboni 1999] it facilitates the use of simulation coupled directly to these systems. This integration will increase the information base since most ERP systems contain the necessary amount of data for detailed production planning [Musselman et al. 2002]. It will also increase the usefulness of the system. Some of the above mentioned examples of simulation based scheduling already have this connection. A Finnish consulting company has for example incorporated simulation and its own middleware into a producing company and is currently doing so in another [Appelqvist and Lehtonen 2002]. McNally and Heavey [2002] describe another case, where data from the business system is migrated to the DES system and results migrated back.

4.9 Summary of simulation

Several authors have described how to conduct a successful simulation study. All of them stress the need for a structured approach from the beginning. Some of the steps in a simulation study are considered to be more time-consuming than others and some to be more crucial for the outcome from the experiments. Much of the ground rules of simulation modelling are the same when simulating energy use and are the base for successful modelling and simulation whatever the goal is. One of the most common used methods for conducting a simulation study has been used for comparison when describing key features in the described methodology.

Simulation use in industry has increased and the areas of application have widened. Greater computer capacity and increased interoperability between different systems have meant that integration between simulation software and other systems such as ERP systems has increased, in turn also increasing the possibilities for simulation within the operative work such as energy management.

Surveys show that DES is used to a relatively small extent in manufacturing industry. The automotive industry is a frontrunner as regards use of simulation in general where DES plays an important part. The foundry industry is not a major user of DES but interest is growing. However, other simulation tools are more commonly used in the foundry industry, mainly different types of casting simulation. Hence, there is a potential for increased use of simulation in the foundry industry. The foundry industry is an energy intensive industry making simulation of energy use visible as a tool with great potential of improving energy efficiency in that industry.

In conclusion, this chapter has described the scientific reference frame within simulation in general and DES in particular that is currently used in the Swedish foundry industry, which is the focus area of this research. The review shows past and current use and views on future use of DES. The research described in this research study has used theories and practice described in this chapter to be able to supplement the use of DES in the future.

5 Methodology for energy management using simulation

This chapter describes the proposed methodology for analysing energy use with DES. The methodology is described from an energy point of view and it is assumed that the user of the methodology is familiar with simulation modelling methods in general terms, also described in chapter 4. Further does the methodology focus on electricity use because most of the processes in most foundries use electricity as energy source. The main processes in a foundry are furnaces, moulding machines, transport systems and support processes such as ventilation and lighting. All these processes use exclusively electricity in most foundries. Hereafter the methodology will be described from the point of view that all processes considered are driven by electricity. Only to a very small extent are processes, at the studied foundries, driven by other energy sources, such as oil or LPG. These processes are for example heat systems or ladle heating. Tests have been made including these as well but future work is needed to show if the methodology work for all such processes.

The methodology follows to a large extent the chronological order of the general steps for a simulation study originally presented by Banks et al. [2005]. The activities that are described are additional activities needed to conduct a study of electricity and power use, using DES. Figure 17 shows the steps in the methodology, where the core activities lie in the conceptual and the translation phases. In these phases it is described how categorisation of processes based on historical electricity data can be made. Based on the categories it is described how states in the simulation model can be used to manage electricity use and to calculate both power use levels and electricity use. Activities are also needed in the preface stages, during the problem formulation and setting of objective. The methodology also gives information about what experiments that can be conducted and what type of analyses that can be made.

This chapter will first give some brief information on when the methodology is useful in the overall energy efficiency work and what strength of DES that are used to formulate this methodology. The methodology is thereafter described and discussed.

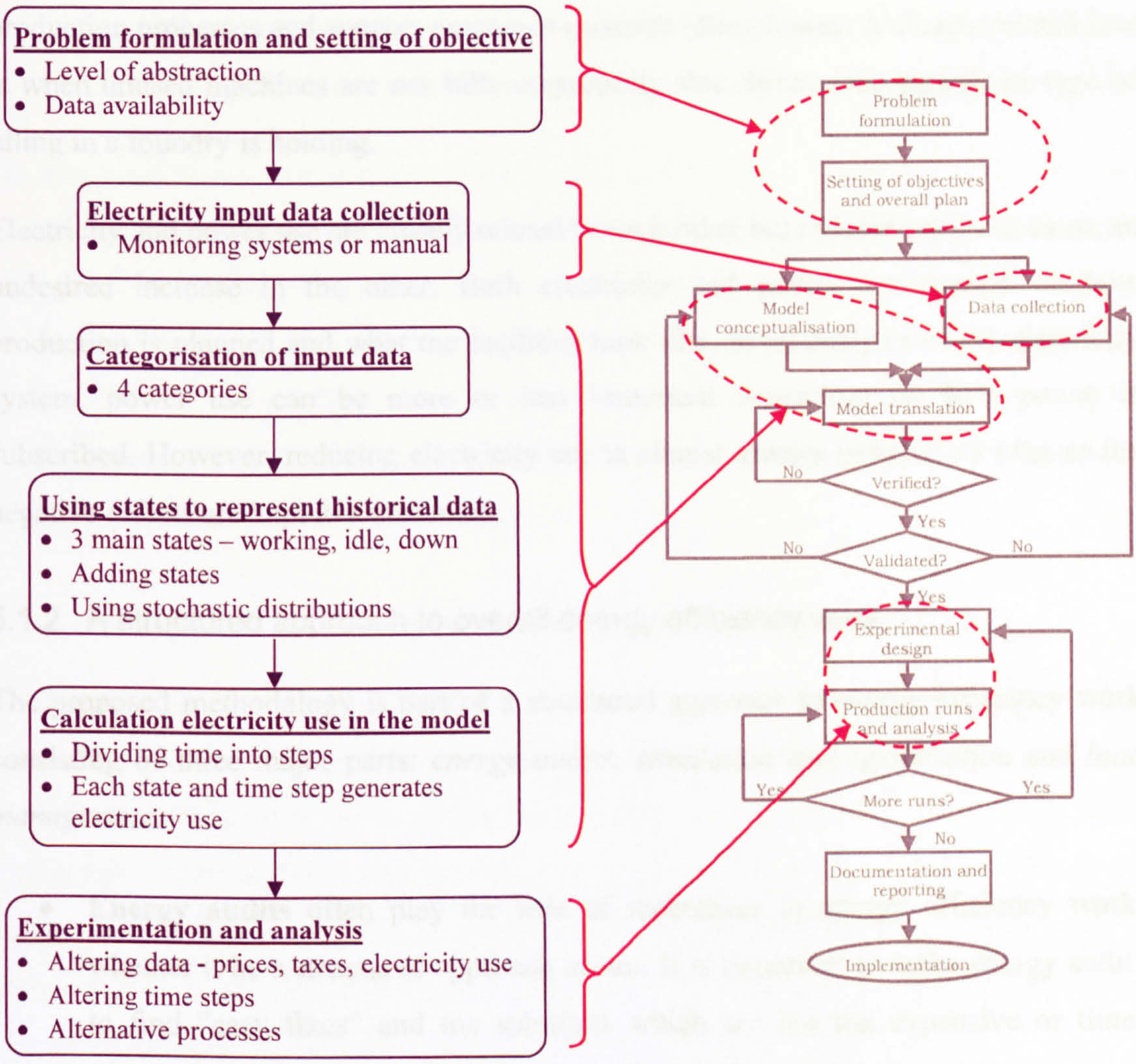


Figure 17.Main steps in the proposed methodology. (Comparison is made with general steps in a simulation study [Banks et al. 2005] on the right.)

5.1 Context and pre-understanding

5.1.1 Main problem areas

Furnaces are generally the most electricity intensive equipment in a sand casting foundry. The furnaces are mainly of two types, melting and holding furnaces, but often a furnace acts as both a melting and a holding furnace. There is often a complex relationship between the melting furnaces, the holding furnaces and the moulding line or department. This can cause interruptions in the utilisation of the equipment.

Idling is often a more electricity using stage than it appears. Idling occurs during work hours, but off-hour losses are also of importance as regards total electricity use. Both production processes and support processes generate idling losses. A closely related loss is when unused machines are not fully or properly shut down. One significant type of idling in a foundry is holding.

Electricity and power use are closely related to each other but reducing one can cause an undesired increase in the other. Both electricity and power use depend on how production is planned and what the facilities look like. In an analysis of the electricity system, power use can be more or less important depending on how power is subscribed. However, reducing electricity use is almost always positive, as long as the negative effects are kept to a minimum.

5.1.2 A structured approach to overall energy efficiency work

The proposed methodology is part of a structured approach to energy efficiency work consisting of three major parts: *energy audits*, *simulation and optimisation* and *load management*.

- **Energy audits** often play the role of icebreaker in energy efficiency work, whether it be a structured approach or not. It is important to make energy audits to find "easy fixes" and the solutions which are not too expensive or time-consuming. Common solutions are finding leaks in compressed air systems, analyses of existing engines and pumps, idling losses and other losses due to poor guidelines and hence inefficient working methods.

- **Simulation and optimisation** have the ability to find the complex correlations that make up production. With simulation it is possible to solve system problems that can not be analysed with the human brain such as changing behaviour of the system depending on changes in input or planning.

- Due to the dynamics of production and last minute changes, simulation will not cope with the actual use of electricity and power as they occur in real time. A **Load Management System** (LMS) is therefore a solution that will help force down peaks that can occur even though a simulated plan shows it should not. This is due to the way the fees for power use are calculated. However, an LMS should be used with caution if simulation is used as well since these systems are not able to analyse the system behaviour for the coming time period, only to make a mathematical calculation based on historical information.

As described above, simulation and optimisation techniques act as advanced tools for analyses of energy systems. Simulation and optimisation can be used for analysis in both short- and long-term perspectives, while energy audits are mostly used in a long-term perspective and load management is a control mechanism for a very short-term perspective. For simulation and optimisation several different types of models and methods can be used, as described in section 3.6, and the described methodology is an addition to that set.

5.1.3 Strengths of DES used when conceptualising the methodology

As described in section 3.6.2 there are traditionally a large number of energy models used analysing the efficiency of an energy systems. Similarly, there are models used to analyse the productivity of a production systems. Analysing both productivity of a production system and the corresponding energy system has not been described in detail in literature. DES has advantages to other modelling and simulation techniques when it comes to for example adaptability and visualisation. The strength of DES used to realise the methodology is listed in the bulleted list below.

- **Adaptability** - Discrete Event Simulation has large potential when it comes to custom fitting. Normally only discrete systems are simulated but there are possibilities to include also continuous parameters. This potential has been used when handling electricity use, which is continuous. It has been solved by calculating the duration between events and setting a value to a parameter for that duration or part of that duration.

- **Programming** - Most DES programs have a programming language of their own, and/or possibilities to add code from other programming languages such as C++. These programming possibilities make it possible to add new functions of choice to the programs. This has been used to make new building blocks in the programs for the analysis of electricity use.

- **Integration** - DES programs often have built-in connections to other programs for data collection and result presentation. The currently most commonly available and used are MS Office programs but often there are ways to integrate other programs via for example ODBC and OPC connections. In the described methodology there is connection to MS Office programs Excel and Access. Input data are manually fed into the spreadsheet or database but are automatically read into the model.

- **Level of detail** - Due to the level of detail possible to use in DES modelling it is possible to follow every product through the whole production system, which has made DES a useful tool for production planning and scheduling. There are basically two ways of using DES for production planning and scheduling. The first is where a beforehand decided schedule is run through the simulation model and the results are analysed. With the result in mind the planner can make corrections and then alter the schedule. The second is where the model generates the schedule based on certain rules and restrictions. The methodology can handle a low level of detail which makes it possible to plan the production based on both production output and energy use.

- **Visualisation** - DES programs used in this research have good 3D visualisation capabilities. 3D visualisation or even visualisation at all is not mandatory to produce DES models with the described methodology. However, during the verification and validation of the model the visual model is a very helpful aid and also for analysing experiments this visual aid is helpful and has been an important part during the case studies in this research.

5.2 Modelling and simulation methodology

The methodology presented and the actions needed to carry out a simulation study with the presented methodology permeate all the steps in the general method for a simulation study. The electricity focus needs to be present all the way through the project. Issues that need to be addressed specially to be able to conduct a simulation study using the methodology formulated are presented in this section.

5.2.1 Problem formulation and setting of objective

It is always important to formulate the problem, the objective and the plan for a simulation project. To be able to use the main steps in the methodology (5.2.3-5.2.8) there are a few things that the modeller needs to take extra care to:

- Decide the level of abstraction and planning (strategic, tactical or operational) of interest. This determines the level of the data acquisition and what experiments can be conducted.

- Examine to what extent and in what detail it is possible to gather electricity data. This data, if measured in the production, can often be measured with a great level of detail. Objectives can, however, not be set to be more detailed than the input data permits. Consideration has to be taken to the abstraction level decided.

- Determine whether it is electricity use, power use, or both that is of interest. Only if the entire plant is analysed, can the optimisation of power use be made without risk of sub-optimisation.

5.2.2 Electricity input data collection

This part is crucial and decides whether or how the main steps in the methodology (5.2.3-5.2.8) can be carried out. As in most DES case studies the data used as input to the model is based on historical events and is therefore a representation of the historical behaviour of the processes. First of all it must be decided how data is to be collected. Mainly there are two ways – automatically or manually. If the production facility has constant monitoring and surveillance system, measuring power data, these should be used. If not, manual measurements have to be carried out. If an overall energy audit has been made recently this could be used, depending on what level of abstraction decided in an earlier stage. Sometimes in surveillance systems data is measured for groups of processes. If so, it has to be decided if the simulation model can be modelled in the same way or if additional measurements have to be made to break down data into more detail. Some tradeoffs often need to be made to complete a model.

The input data gathering, whether it be energy audit or measuring, is the stage which decides if it is possible to conduct a simulation study or if an audit is all that can be carried out. The energy audit can also show information that will cause a change of focus which will force the team to rework objectives.

The simulation model is dependent on the quality of the information gathered in the energy audit and measurements. It is much more difficult to find errors from measured electricity data than from measured production data. If errors occur during simulation tests, it is not a simple matter to decide if it is the quality of the input data that is poor or the model itself since it is not possible to perform visual tests for electricity and power use during simulation.

As described by Sadowski and Grabau [2000] collecting input data can be very time-consuming and it can be a matter of getting too little, too much or even wrong data. It was found in the preliminary phases of this research that availability of electricity data varied greatly between the different companies. In some cases there was too little data and in one case there was too much, making it difficult to structure. None of the data has been found to be wrong, but there is always a possibility that data might be found to be incorrect at a later stage as a result of new circumstances. Perera and Liyanage [2000] found that *poor data availability* and *difficulty in identifying available data sources* are the main potential pitfalls in these studies. Such pitfalls can be avoided by a tighter linkage between the conceptual model building phase and the data collection phase.

From the definition by Robertson and Perera [2002], two different types of data collection for model building were used; *computer application* (MS Excel) and *intermediary simulation database* (MS Access). The companies involved in the different case studies also use a variety of different programs for data collection, planning and scheduling. This, together with the fact that two different simulation programs were used, made it too time-consuming to consider integrating every combination of these programs, which is why integration has not been prioritised.

The behaviour of the LMS and power limits need to be explored. Analysing situations when the LMS has interfered can be useful when building the model and when designing experiments. It is also important to analyse how the production affects the electricity use of one process or a group of processes, an analysis that will be somewhat biased from the modellers point of view. The analysis therefore has to be validated by the system owner. The information from this analysis has to be built into the model.

5.2.3 Categorisation of input data

Before modelling it must be decided how input data should be modelled and used in the model. It must also be decided how output data should be represented. As opposed to traditional input data such as cycle times and down times electricity data is continuous and more complex as regards to modelling. When analysing input data from energy audits and measurements it was found that there is not only one way to represent electricity input data. Instead four main categories were identified among the vast amount of data analysed. Below are descriptions of these different categories and examples of how they look when visualised in graphs. All categories are validated by examples from measurements from the plants later described in the case studies. It should be noted that there might exist other categories at other production sites.

1. **A stochastically represented load when working, while idling and while off.** This regime works with equipment which requires no electricity when it is not working. However, this is not true of equipment that has warm-up times or fluctuations in use during work. Examples of this category are shown in Figure 18 and Figure 19.

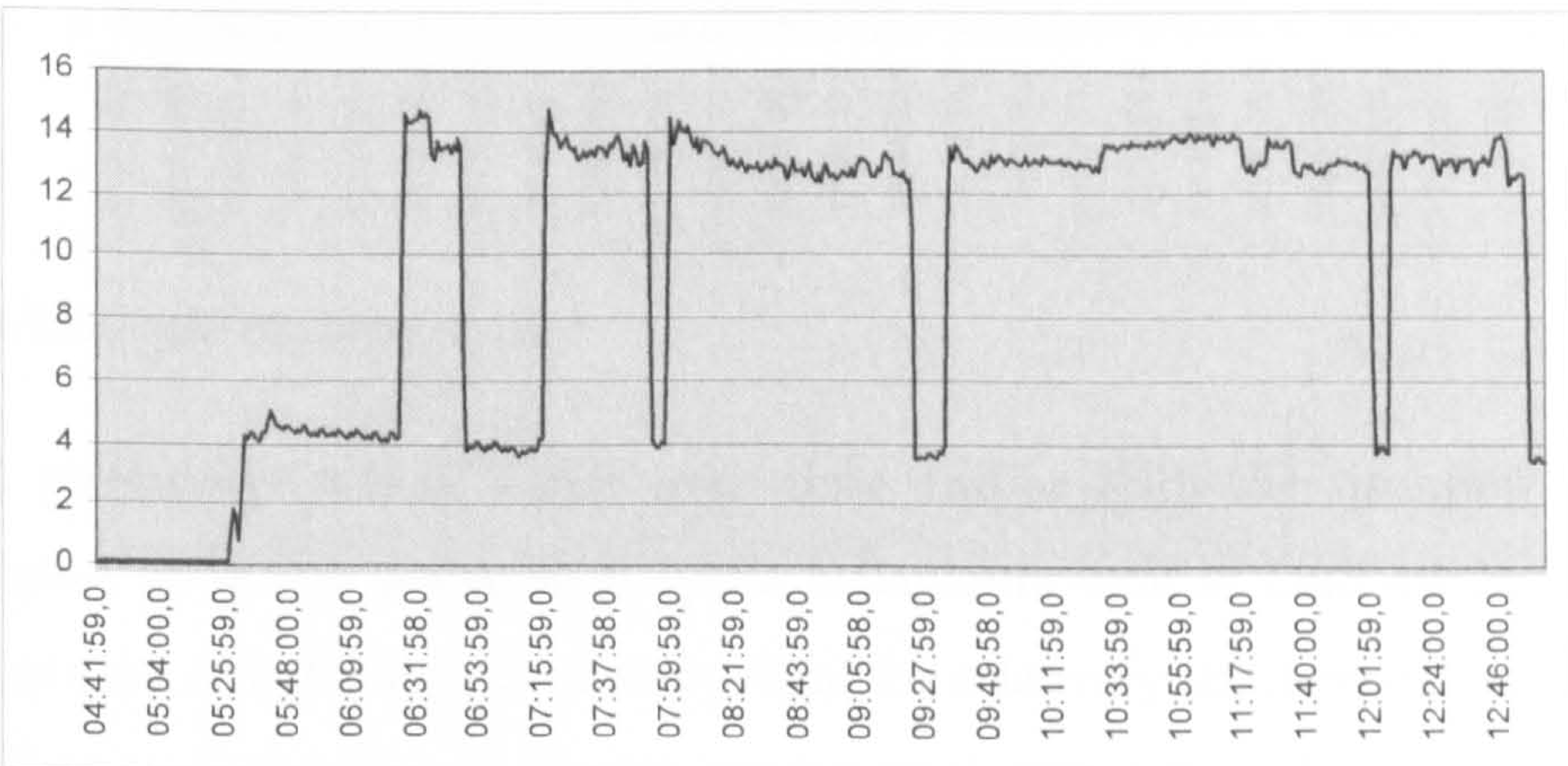


Figure 18.Example of category 1 with three different states.

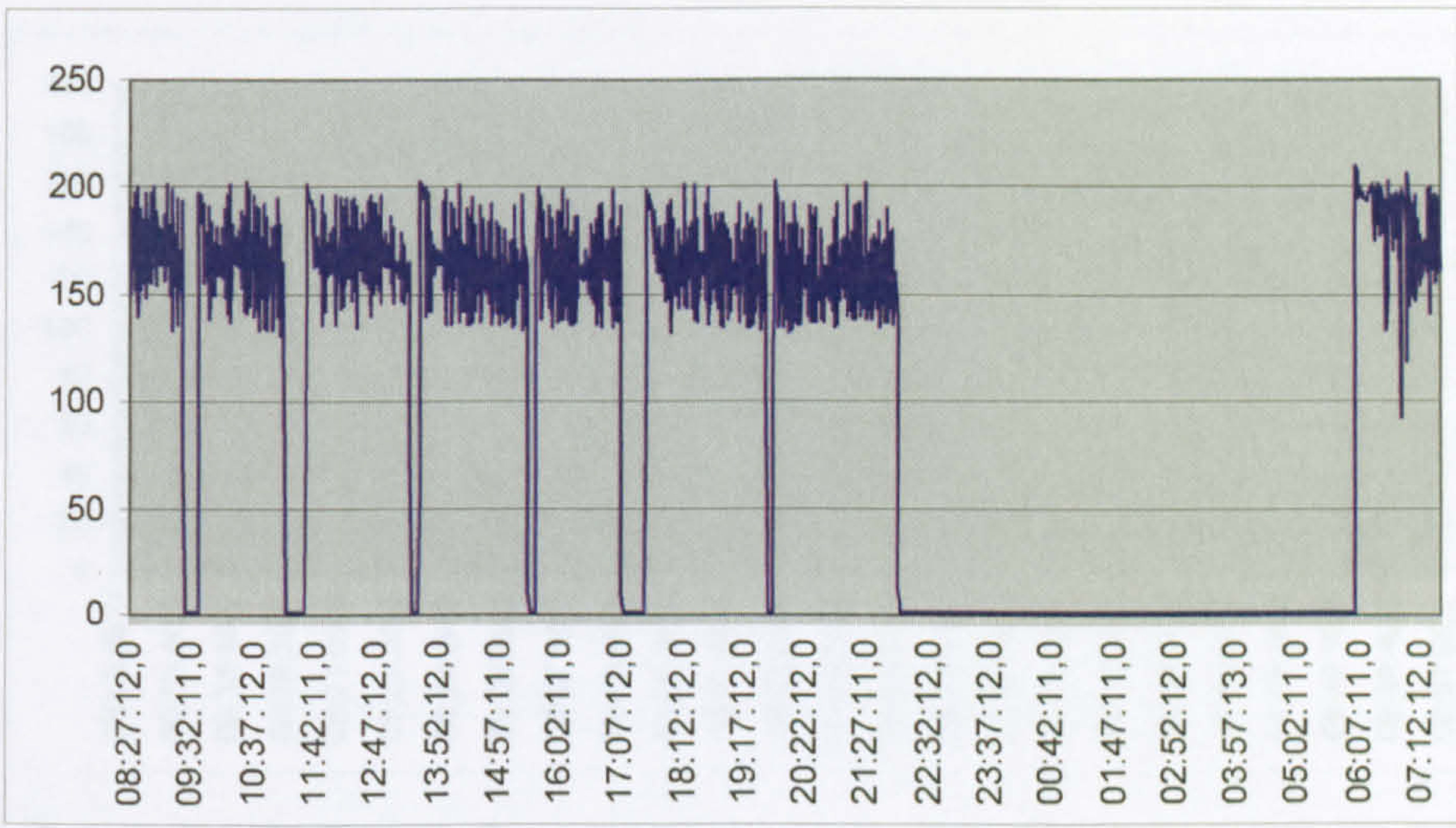


Figure 19.Example of category 1 with two different states.

2. **One stochastic representation during simulation.** Works with processes that have the same representation whether there is production or not. Heating can sometimes be represented this way if heating is needed to also keep the buildings warm at night and during cold periods. An example of this category is shown in Figure 20.

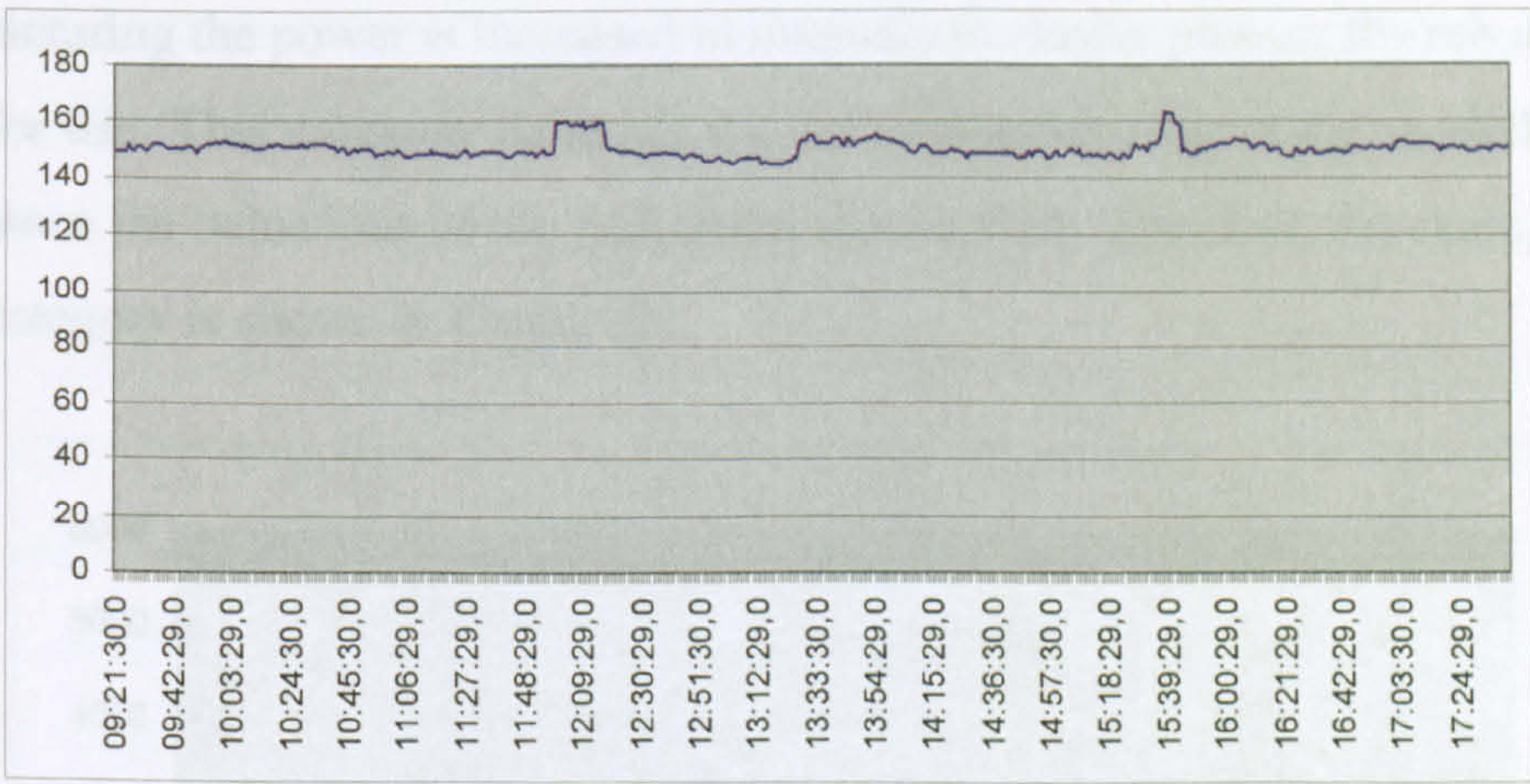


Figure 20.Example of category 2.

3. **A parameter which varies over time and/or with the situation.** This type shows up in equipment with cyclic behaviours such as sand mixers. However, this type of behaviour is often cyclical for relatively short periods and therefore often has only a small impact on the total output behaviour of the plant. An example of this category is shown in Figure 21.

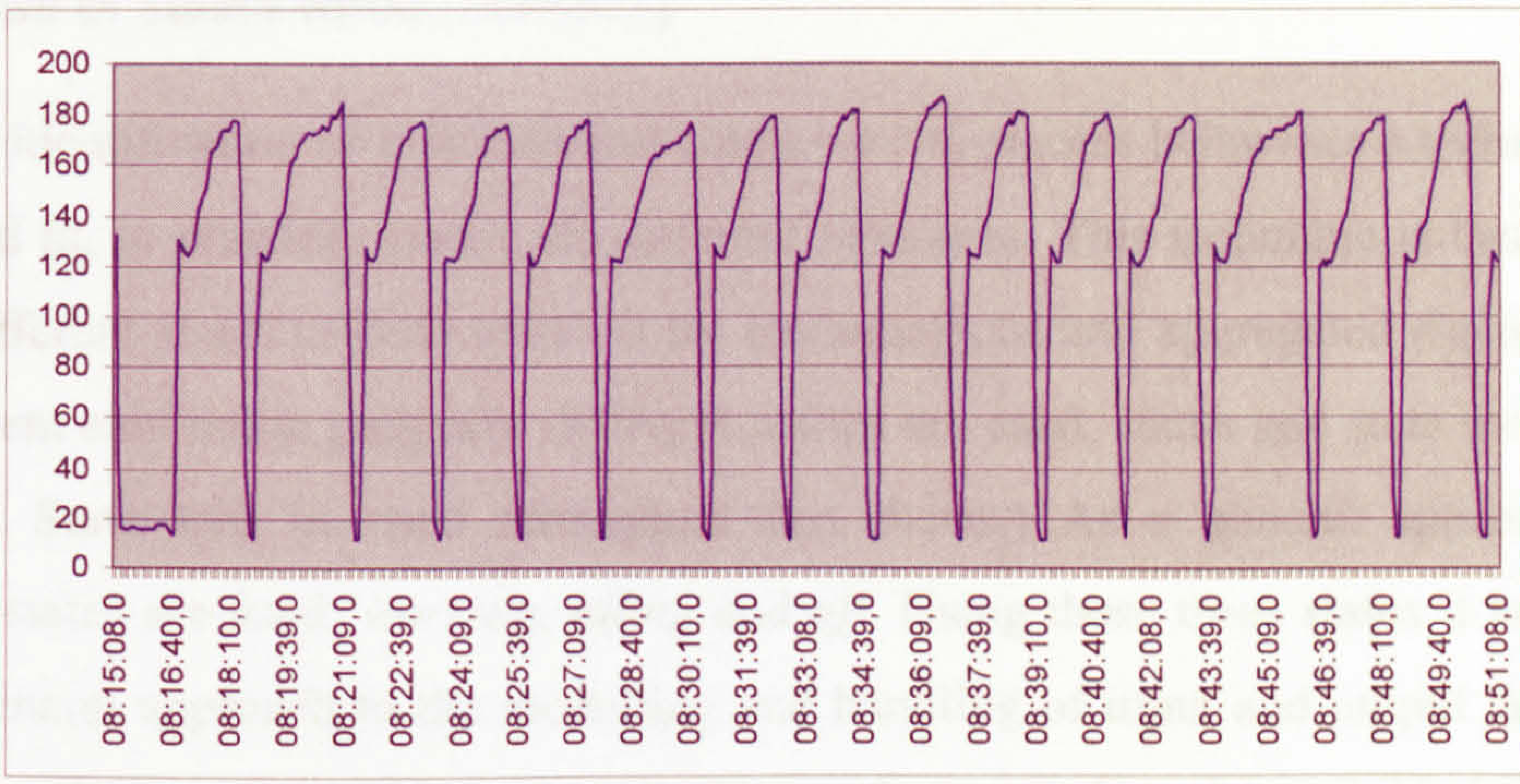


Figure 21.Example of category 3.

4. **A special logic, due to special or complex use of the resource which does not fit into the first three categories**. This works with processes where the use of the resource is based on several manual decisions and not on a standard foreseeable pattern. Melting is one such process where in the main full power is used but when a certain temperature is reached the power is reduced. Sintering a furnace is an example of another situation where this approach is used. During sintering the power is increased in intervals to slowly prepare the rebuilt furnace for use. This category demands the most programming in the modelling phase since the behaviour of the equipment can be fairly complex. An example of this category is shown in Figure 22.

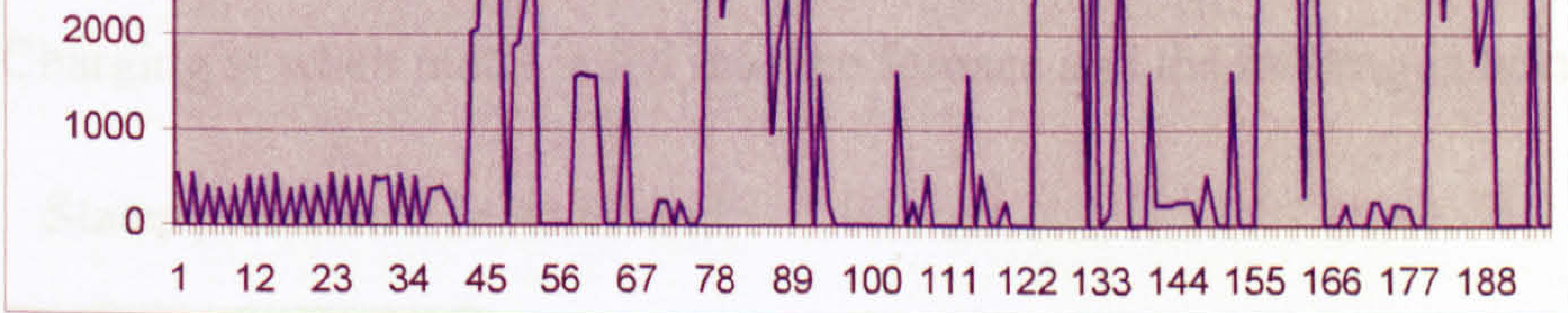


Figure 22.Example of category 4.

5.2.4 Use of states when modelling

From the identification of four different categories of process behaviour a technique was developed to, in practice, model the different resources. This technique is based on the use of different states to keep track on the instantaneous and aggregated electricity use. (In different simulation programs different names are used, status and state are the most common. State will be used throughout this thesis.) As a general approach three different states are used: *working*, *idling* and *off*. Using these three states it is easier to keep a general approach to the modelling and handling of input and output data. Some adjustments have to be made to some processes, for example melting and holding which belong to category 4. The adjustments for the furnaces were made by adding extra states, such as charging and testing. In these cases the power used was handled by algorithms in the model. However, it is very important to have a good knowledge of the DES program used. Different programs have different predefined states. Some programs have none, and some several. Especially when using predefined logic for handling events in the model, resources can enter states that are not expected, resulting in false results. Hence, the modeller should always keep track of which state the resource is in. One way of keeping track of this is by categorising all predefined states into the three groups described earlier: working, idling and off (see example in Table 5). Another way is to only use states defined by the modeller and not use predefined logic.

In the two programs used, AutoMod and ED, there are predefined states available to use. In AutoMod there are three different states, see Table 2. In ED there are 33 different states predefined, see Table 3. However, additional states are needed to break down the use of the furnace into more detail since there are two more states that come out clearly while analysing the use of furnaces. These states are holding and charging, se Table 4. Holding is when metal is held at a predefined temperature after melting is finished. Charging is when metal is fed into the furnace and the melting is interrupted.

Table 2. States predefined in AutoMod.

Number in state list	State name
1	Processing
2	Down
3	Idle

Table 3. States predefined in ED.

Number in state list	State name	Number in state list	State name
1	Idle	18	Open
2	Busy	19	Closed
3	Down	20	Waiting for Contents
4	Waiting	21	Waiting for Package
5	Blocked	22	Collecting
6	Travel Full	23	Content Blocked
7	Travel Empty	24	Distributing
8	Lift Up	25	Busy and Blocked
9	Lift Down	26	Conveying
10	Not Down	27	Setup
11	Available	28	Waiting for Job
12	Not Available	29	On the Job
13	Empty	30	Waiting for Operator
14	Full	31	Assigned
15	Not Empty	32	Take-Down
16	Load	33	Travel to Job
17	Unload		

Table 4. Additionally user defined states in AutoMod and ED.

AutoMod	
Number in state list	State name
4	Holding
5	Charging

ED	
Number in state list	State name
34	Holding
35	Charging

In AutoMod these three predefined states and the two additional states are easy to use and to keep track on. In ED however the 33 predefined states were collected into the three groups (working, idling and off) to make them fit into the four categories defined, see Table 5. This is a simplification which makes it possible to fit all processes into the four categories defined. The deviation from reality this simplification brings can be kept to a minimum by always setting the processes into a specific state at every event. However, for most processes this is a too time consuming operation. But for processes with additionally defined states, such as the furnaces, it is mandatory.

Table 5. States groups into working (W), idling (I) and off (O) in ED.

Number in state list	State name	State group	Number in state list	State name	State group
1	Idle	I	18	Open	I
2	Busy	W	19	Closed	I

3	Down	O	20	Waiting for Contents	I
4	Waiting	I	21	Waiting for Package	I
5	Blocked	I	22	Collecting	I
6	Travel Full	W	23	Content Blocked	I
7	Travel Empty	W	24	Distributing	I
8	Lift Up	W	25	Busy and Blocked	I
9	Lift Down	W	26	Conveying	W
10	Not Down	I	27	Setup	I
11	Available	I	28	Waiting for Job	I
12	Not Available	O	29	On the Job	W
13	Empty	I	30	Waiting for Operator	I
14	Full	I	31	Assigned	I
15	Not Empty	I	32	Take-Down	I
16	Load	I	33	Travel to Job	W
17	Unload	I			

5.2.5 Adding states

As mentioned in previous section, additional states were needed to handle the behaviour of the processes when modelling. Adding states are handled differently depending on the program used.

In AutoMod states has to be added in beforehand via the Graphical User Interface (GUI), see Figure 23. It is also possible to add different states to different processes which should be used with care since it might be difficult to keep track of which states belongs to which process. In the case studies described in this thesis a common set of states was used for all processes.

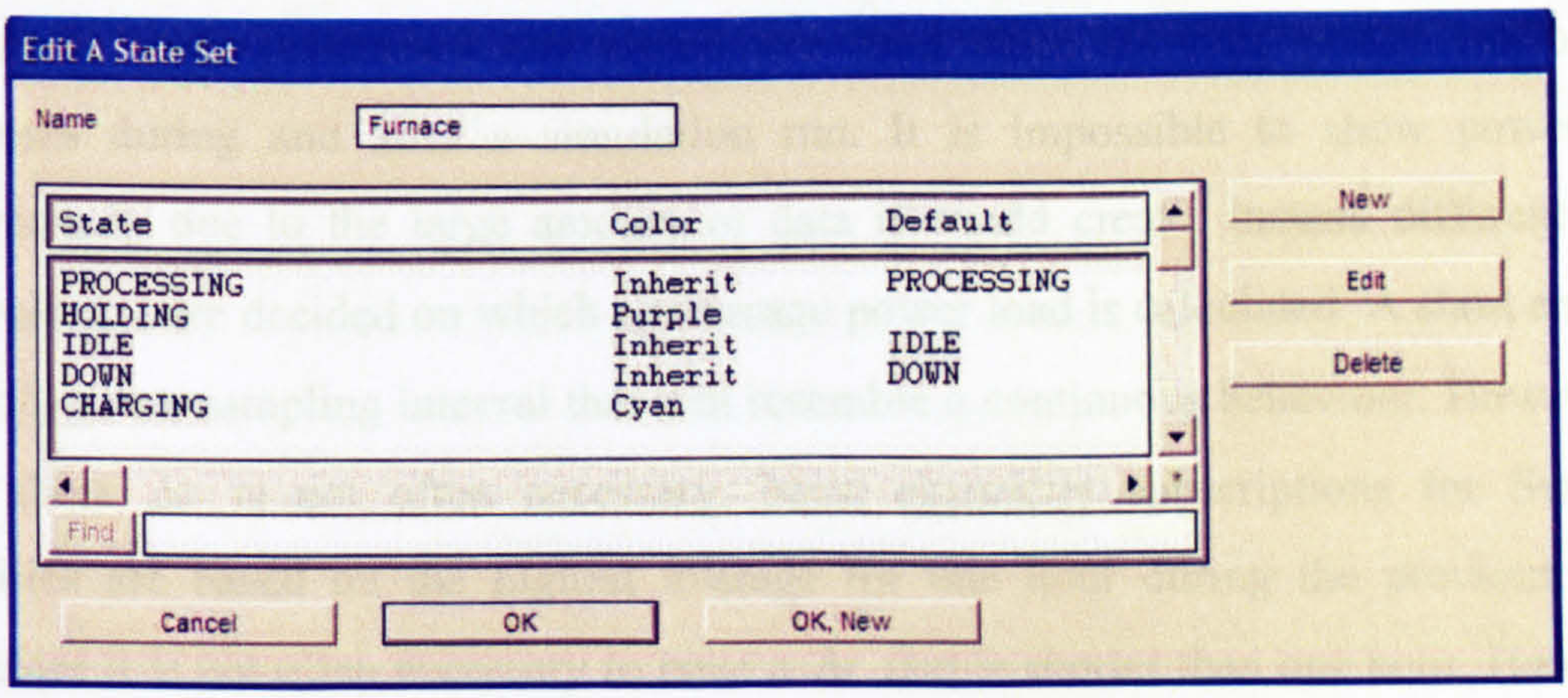


Figure 23.Adding states in AutoMod

In ED it is possible to add and remove states as the simulation progresses through pre-programmed code. It is also possible to interactively change states of resources in the model if needed. To add a state in ED a line of code is needed. Below are the two examples of how that is done. The state is defined when it is used for the first time.

```
Status(c):=34          {Holding}
```

or

```
SetStatus(34, c)      {Holding}
```

In the examples above "c" is the current atom. Atom is the name for an object in ED. In the above case there is a state added to the furnace which is called Holding where "{Holding}" is a comment. The name of each added state needs to be remembered by the programmer. One way to do that is to add a variable that can be referred to when needed by using the following code:

```
GlobalVar([StateHolding], vbvalue, 34)
```

where "StateHolding" is the name of the variable, "vbvalue" means that the type of the variable is a value and "34" is the value of the parameter, which in this case is the first available number, since there are 33 predefined states.

5.2.6 Using states to calculate power loads

The states, both predefined and added, are used when showing power use of the processes during and after a simulation run. It is impossible to show power use continuously due to the large amount of data it would create. Instead different time intervals, Δt, are decided on which an average power load is calculated. A short enough Δt will give a sampling interval that will resemble a continuous behaviour. However, a very short Δt is not often necessary. Most electricity subscriptions for Swedish foundries are based on the highest average for one hour during the previous year. Therefore it is not often necessary to have a Δt that is shorter than one hour. However, when a more detailed analysis of the behaviour of the system is needed or if a LMS is emulated, a smaller range is preferable.

During one Δt it is possible for a process to be in more than one state. Therefore the time the process has been in a specific state has to be calculated for all states and for all Δt during the run. For calculating the average load for a process during one Δt and for the most common states working, idle and down, equation 5.1 can be used.

$$\frac{x \bullet W}{\Delta t} + \frac{y \bullet I}{\Delta t} + \frac{z \bullet O}{\Delta t} + \ldots = L \qquad (5.1)$$

where L is the total average load, x,y and z is the time the process has been in each state during Δt, W is load while working, I is load while idling and O is load while off. If additional states are used these are added as well.

Where power load for each process is a constant this constant is used directly in the formula. However, when input data is more detailed, so that each state is represented by a stochastic distribution, the distribution is used. But the distribution can not be used directly in the formula due to the possible large variations of output from a distribution sample. Instead a mean of several distribution samples are used for longer sample lengths. There are two ways of doing this in practice:

- In the first solution, the simulation user decides before a run how long every time step should be for sampling output data. He also decides what the shortest time step is for only using one sample. 5 minutes between each sample is a usable length for this application. In the formula below these variables are collected from the user and fed into the formula. The number of values for calculating a mean value is then rounded to an integer. A longer Δt will result in more samples and a more stable solution.

  ```
  GlobalVar([NrOfValuesForMeanSampling],vbvalue,Trunc(Tim
  eBetweenSampling/ShortestTimeForOneSample)+1)
  ```

  This solution is very flexible and will always give the user the amount of data wanted and will present it in the way the user wishes. There are no limitations for how long or short a time step must be. However, every time a new time step is desired, a new simulation run has to be conducted. Using this solution most of the calculations are made in the simulation program before exported to for example a spreadsheet.

- In the second solution the choice of length between intervals shown to the user is decided at a later stage, after the simulation run. The model is instead programmed to sample every Δt so that a larger number of state samples are made every run. 5 minutes between each sample is a usable length for this application. Every 5 minutes a sample time for each state is calculated. This sample is multiplied with the distribution sample for each state and all states are then added to determine the average power load for each Δt. The advantage of this solution is that the model does not need to be rerun when more or less information is needed in the graphs. But this solution is not flexible if the user wants a graph more detailed than the smallest Δt or a multiple of Δt. It also generates more output data than the first solution, which may slow down the simulation.

In both these solutions, each state during a Δt is multiplied with at least one sample from a stochastic distribution. However, when the length of Δt is longer there are several distribution samples for each Δt which evens out possible samples that are close to the edge values for a distribution. The calculation will then instead look like in equation 5.2.

$$\frac{x \bullet \frac{\Sigma W_1 ... W_n}{n}}{\Delta t} + \frac{y \bullet \frac{\Sigma I_1 ... I_n}{n}}{\Delta t} + \frac{z \bullet \frac{\Sigma O_1 ... O_n}{n}}{\Delta t} + ... = L \tag{5.2}$$

where L is the total average load, x,y and z are the time the processes has been in each state (x=working, y=idle, z=off) during Δt, n is the number of distribution samples, $\Sigma W_1 ... W_n$ is the sum of n numbers of distribution samples for the load while working, $\Sigma I_1 ... I_n$ is the sum of n numbers of distribution samples for the load while idling and $\Sigma O_1 ... O_n$ is the sum of n numbers of distribution samples for the load while off. If additional states are used these are added as well.

Figure 24 and Figure 25 illustrates how different Δt affects the visualisation of output data in graphs. The two graphs show the result from the same run but with sample lengths of 1 hour and 5 minutes respectively.

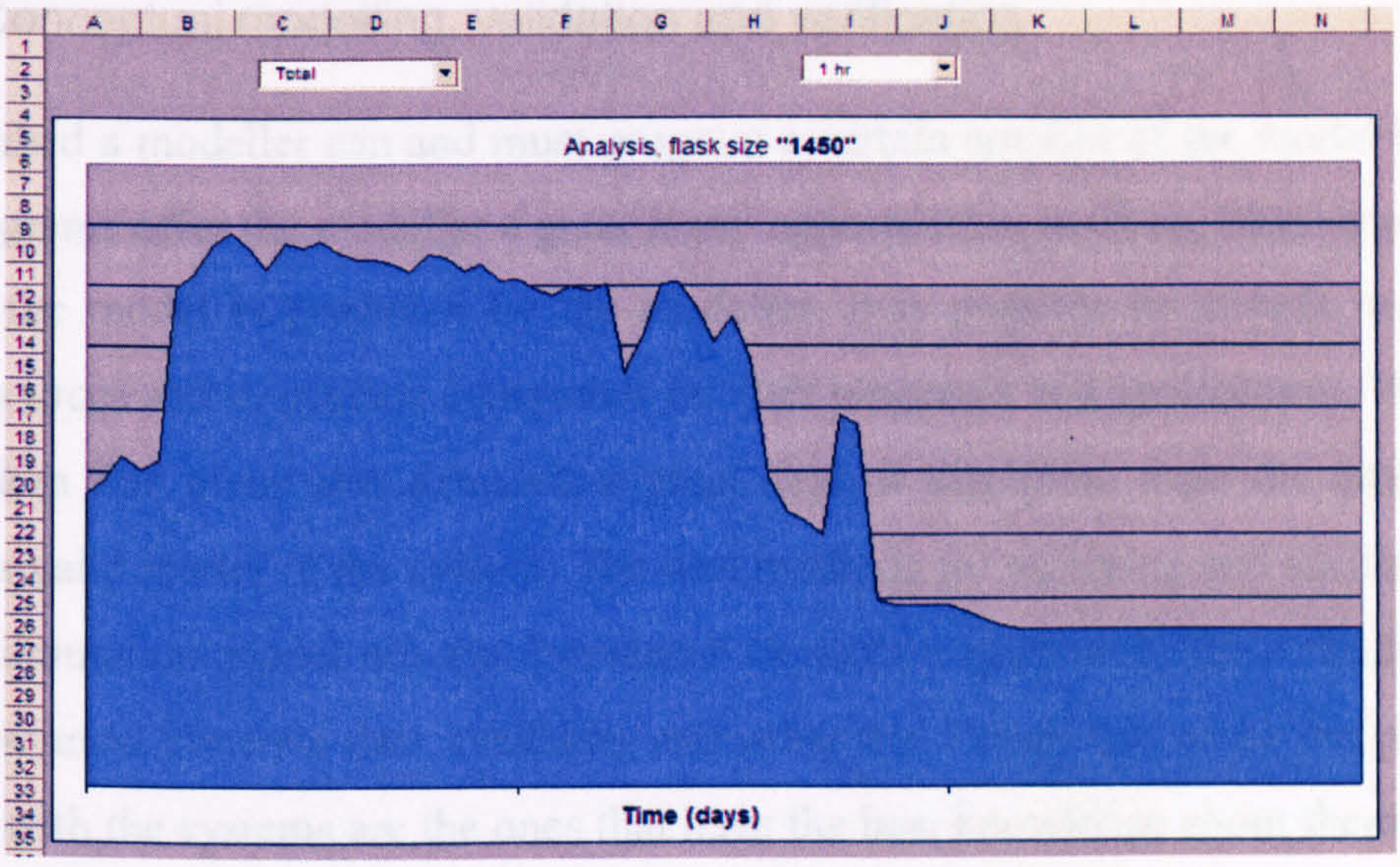


Figure 24.Average energy use for intervals of 1 hour.

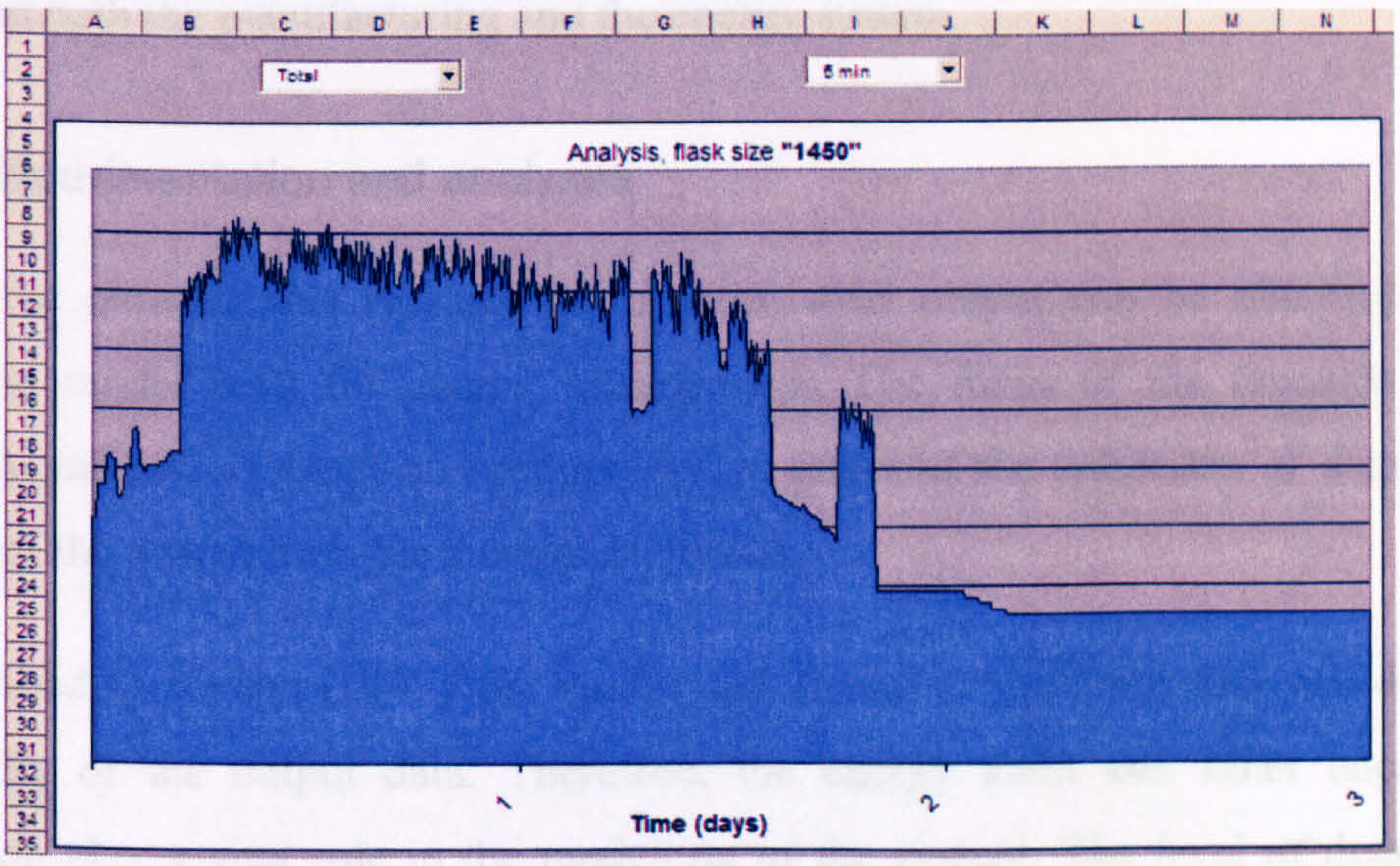


Figure 25.Average energy use for intervals of 5 minutes.

At the end of a run it is interesting to look at the total electricity use during the run or during a predefined period such as a month. To do this every mean power load for each Δt is added together according to equation 5.3.

$$E_{tot} = \left(L_1 + \ldots + L_n\right) \cdot \Delta t \tag{5.3}$$

where E_{tot} is the total electricity use and L_1 to L_n are the mean power loads for each Δt within the studied time period.

5.2.7 Conceptual modelling, validation and verification

As described a modeller can and must program a certain amount of the model by hand. DES programs offer the modeller a great many opportunities to do so. Since most of the logic in the model is produced by the modeller, it is possible to include code from outside sources and to execute commands in other programs and applications. However, the freedom this gives also demands a great deal of discipline from the modeller to achieve a valid model of the system. The best methods for verifying and validating this type of simulation model are the *correlated inspection approach*, since the historical data is the most concrete data available, and using the *Turing test*, since the personnel working with the systems are the ones that have the best knowledge about them. For the Turing test different people need to be involved because the same people might not be experts on both the manufacturing and the energy system.

5.2.8 Experimentation and analyses

One of the aims of this research is to show what output can be obtained from a simulation model built for energy management. The focus of the research was on electricity and not so much on productivity, in terms of the collection of data and the analysis of the output from the simulation model.

As described by Kelton [1997], the quality and format of the input data will determine the quality of the output data. Therefore, the energy audit and other energy data acquisition play a vital role in the modelling of the system. The level of detail of the input data will ultimately determinate the possible level of abstraction of the simulation model and the level of detail of the output data.

Spreadsheet programs, such as MS Excel, have good functionality when it comes to visualisation of data in different formats. The most commonly used in simulation are graphs of various kinds.

It is important to identify early on what is of interest to analyse and make output available accordingly, since no two simulation projects are alike. It is also important to define which parameters should be able to be varied (and to optimise if optimisation is an aim). The different types of information that have been identified as most important in this study are:

- **To be able to change the power use of processes,** either manually or automatically due to the situation in the simulation model or if a process is altered in some way. To do it automatically may be a way to simulate the LMS of the facility but one has to be aware that the simulation model will not behave exactly as the system at any particular moment. It can therefore be more harmful than beneficial to simulate the behaviour of the LMS since the restrictions the LMS puts on the facility's processes will change other parameters, which are difficult to predict.

- **To be able to alter electricity prices.** These may vary during the day, the month or the year depending on the type of subscription and market fluctuations. To be able to alter electricity prices alternative production schedules or alternative shifts can be simulated and analysed. For example if the price is higher during the day it might be economically beneficial to melt during the night and morning and hold it during the day. That scenario will probably result in a higher electricity use in total but a more even use during the day which will be appreciated also by the grid owner.

- **To be able to choose between different tax levels and other related costs** such as costs related to the EU ETS and the ECS. As in the previous example this can be used to evaluate how different taxes and costs will affect the total cost of running the production system.

- **To be able to define the length of the output interval.** It is not possible or practically usable to show power use continuously due to the large amount of sample data it would demand to be stored and managed. Depending on the use of the model different levels of detail is needed for the graphs representing power use. Since most subscriptions are based on the highest average for an hour, that interval is usable in many cases. This is described more in section 5.2.6.

Additionally, there are some parameters that are of interest when conducting projects with a special focus, which are described in the following bulleted list. However, such scenarios will need additional modelling or use of more than one model.

- **To be able to choose between different energy sources,** such as electricity, oil or others. An example would be heating which in several facilities can be made with electricity, district heating or oil. Sometimes one or the other is cheapest. Sometimes it might even be more economically beneficial to use oil driven heat generator for a short while during the end of an hour when the subscription peak load is emerging. Doing so may help the company stay below the subscription level and avoid fines and an increased subscription level for the coming year.

- **To be able to use alternative resources** or a different number of resources, for example fewer and faster furnaces, if the objective is to find alternatives to existing production equipment.

Notable is also that when running a simulation model for a longer time, days to months, there are periods where several processes, mainly support processes such as heating, cooling and ventilation will change due to outside temperature, humidity etc. This can be handled by applying different stochastic distributions to different periods.

5.2.9 Distinction between production processes and support processes

Normally when modelling energy systems processes are divided into two groups, production processes and support processes [Trygg 2006]. In a foundry examples of production processes are melting, moulding, knockout, shot blasting and fettling. Examples of support processes could be ventilation, space heating, cooling, lighting and compressed air. However, in this research this distinction has not been used. The categorisation described in section 5.2.3 is used for all processes in the studied systems.

The most difficult part of representing the foundry processes is to find the system boundaries for each process and if necessary group them into subgroups. It may also be complicated, but necessary, to know the dynamics of each process. One example is the correlation between twin power furnaces. Twin power furnaces use the same power source and both can therefore not use full power at the same time. Figure 26 shows the use of twin power furnaces in one of the case studies. This power use can then be studied together with the weight curve (Figure 27) and temperature curve (Figure 28) to determine the time it takes to melt a certain amount of metal using a certain amount of power. Furthermore, the people working at the melting shop can explain how the melting procedure usually works and can explain deviations and the specification of the furnace can be studied. This information is helpful when interpreting the graphs.

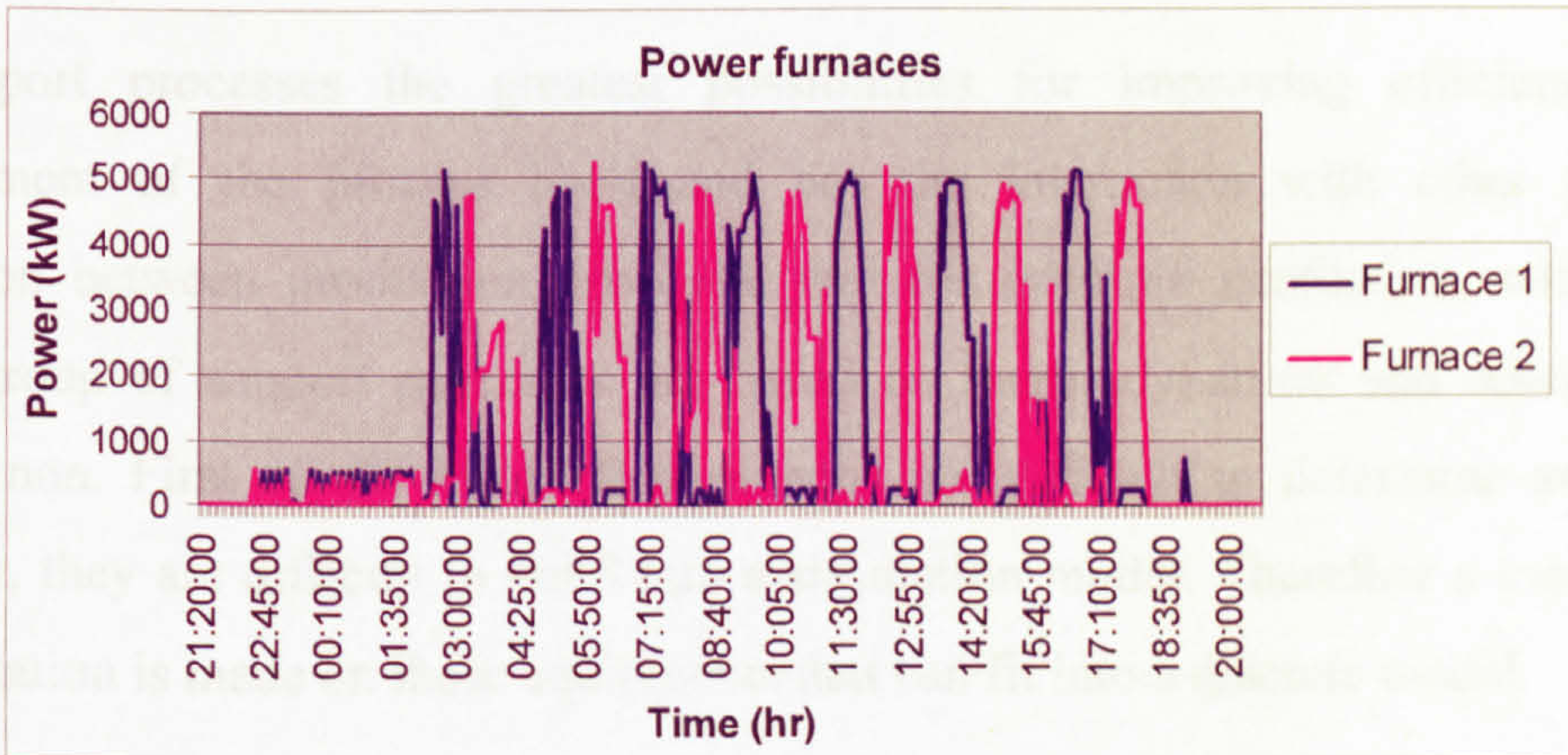


Figure 26.Power use by two furnaces during one working day.

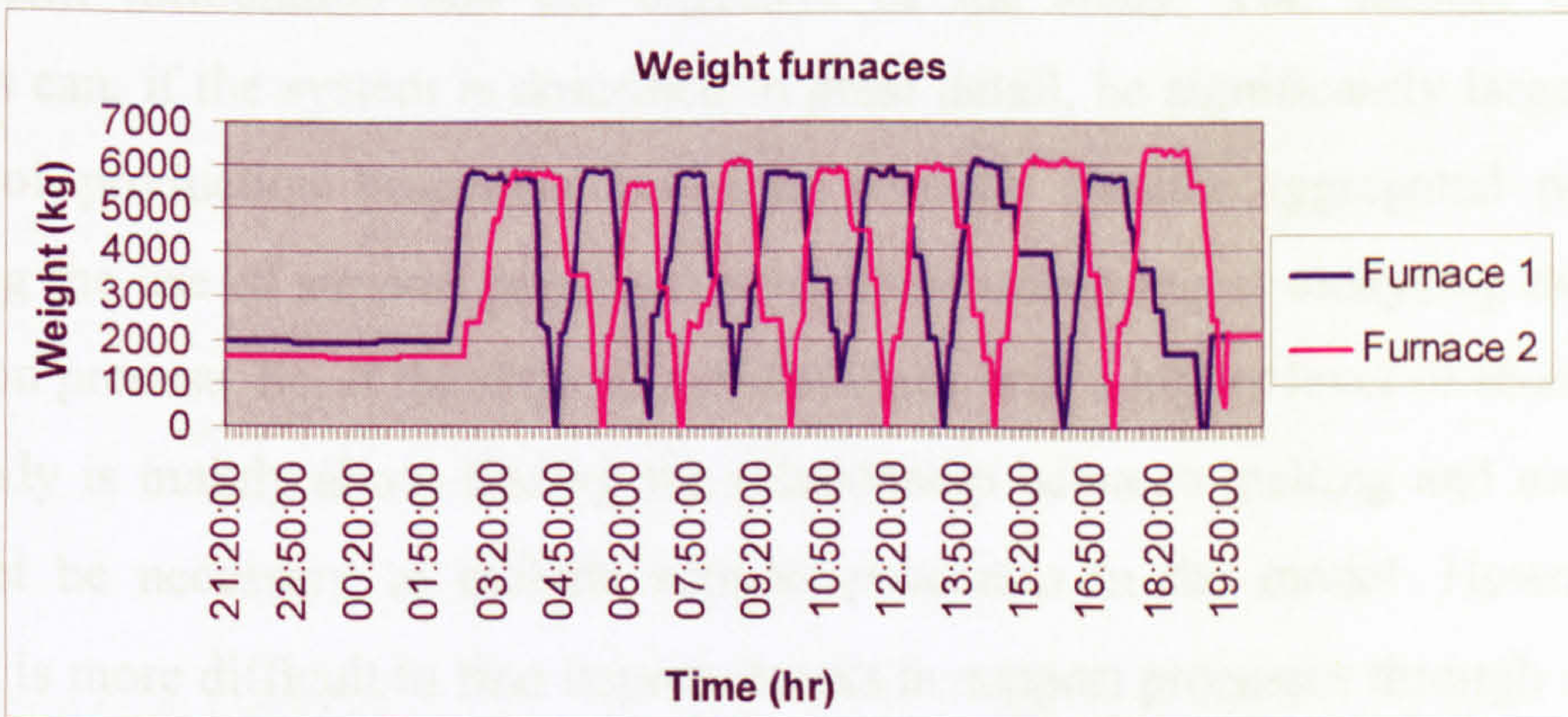


Figure 27.Weight in two furnaces during one working day.

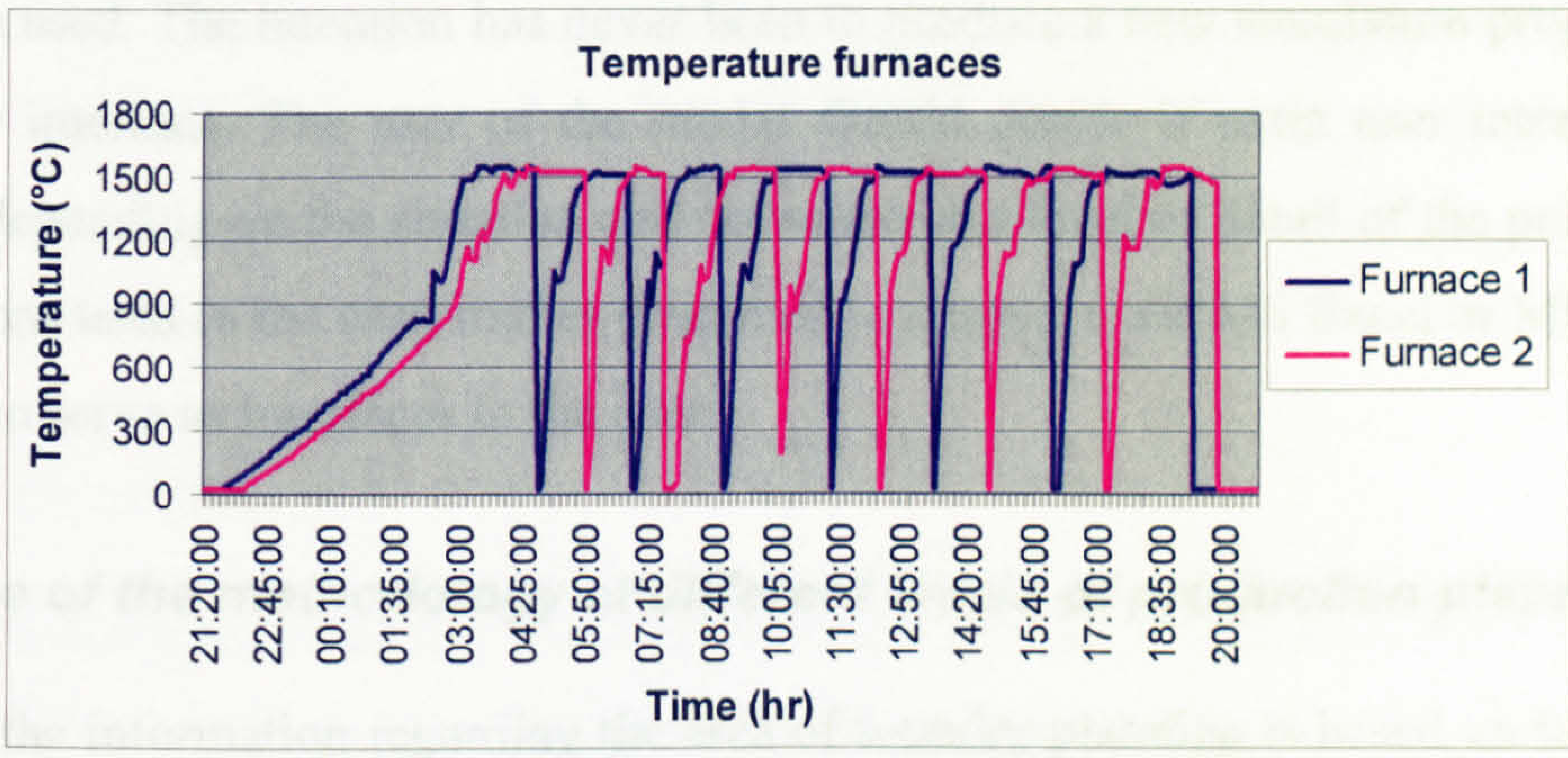


Figure 28.Temperature in two furnaces during one working day.

For support processes the greatest possibilities for improving efficiency lie in improvement of the process itself and not the interaction with other processes. Interaction between production processes and for example ventilation, which is the largest group of support processes are based on thermodynamics and other physical phenomenon. First of all, these phenomenons are difficult to determine and define. Secondly, they are difficult to build into a simulation model. Therefore a more general representation is made on these equipments that can fit into a discrete model.

The analysis of support processes is dependent on the level of abstraction, for example the problem formulation and the objective of the study. The number of support processes can, if the system is described in great detail, be significantly larger than the number of production processes, but with a much smaller aggregated power use. Analysing the use of support processes is as time-consuming as analysing the use of a production process. So, if the objective of the study is at a higher level of abstraction, or if the study is mainly about finding the relationship between melting and moulding, it might not be necessary to include support processes in the model. However, even though it is more difficult to find improvements in support processes through simulation it can serve as a very informative source for showing managers that support processes use a substantial amount of electricity.

5.3 The user interface

All simulation programs have a user interface that is more or less easy to work with. The research study presented makes use of the possibilities that are given in the programs used. The intention has never been to produce a new simulation program or a new user interface. The user of the model should decide if extra user interfaces are needed, depending on the situation and the scope and level of detail of the project. The applications used in the case studies described in chapter 6 are MS Excel or MS Access, which also serve as interfaces to the user.

5.4 Use of the methodology at different levels of production planning

Much of the information regarding the area of foundry planning is based on formal and informal interviews with planners at foundries, mainly in Sweden but also in Norway. In small and medium-sized foundries the information about the foundry production system often exists in the experience of a few skilled people. These people have the ability to put together the bits and pieces to produce a good working production plan. The more complex the system is, the more difficult it is to make an appropriate plan that works well with the entire production system. This kind of information has been invaluable for the work done within this research, both for building simulation models based on the information and for getting the big picture of how foundry systems work. The different types of foundries also present a variant type of planning. Since planning of daily production can vary from kilos to hundreds of tonnes there are different algorithms that work for different foundries.

The methodology devised can be used at all different levels of planning and for many types of analysis, since the level of abstraction can easily be altered by the modeller. The description is based on three hierarchical levels of planning, *strategic*, *tactical* and *operational*, as described by Dewhurst et al. [2001] and Landeghem and Vanmaele [2002].

5.4.1 Strategic planning

In strategic planning the major electricity users are most important. Strategic issues concern substantial investments and changes in strategic product mix. DES has proven to be useful in these phases [Jägstam 2004] and the methodology proposed will help companies calculate Life Cycle Cost (LCC) for investments and calculate how new products will affect the production system and its associated electricity use.

The difficulty here is to decide how to make the analysis for a new piece of equipment. A power load analysis is most useful for looking at smaller time steps while electricity use during a life cycle requires a longer simulation run. Multiple runs are required for these analyses.

5.4.2 Tactical planning

Tactical planning involves increasing productivity at a manufacturing plant. The method proposed will assist in the analysis of the product mix by making an analysis of how the mix will affect the system's electricity and power levels.

This type of analysis must be made together with material and sand specialists since a product mix will also affect sand use and the amount of metal required, which can affect quality too. It might not be possible to produce some product mixes due to limitations in sand and material operations.

In tactical planning the less electricity intensive equipment is of greater interest than in strategic planning. The entire electricity system can be analysed and dimensioned, which has an impact on the power subscription.

5.4.3 Operational planning

For operational planning the methodology described will be most useful when analysing how power levels will vary during production.

A detailed analysis of interactions between different resources can also be made. For example, the interaction between furnaces and moulding lines can be analysed to minimise holding times and reduce the amount of waiting for molten metal.

Making these detailed analyses of power use is hazardous when an LMS is in use. An LMS can be emulated by using the same type of algorithms as the LMS, but this will not give information about how high the peak would actually be. Due to the algorithms for calculating future power demand, the behaviour of the system will change if a peak is impending. This is difficult to simulate. If important resources such as furnaces are forced down, the metals' content and structure will change and more manual decisions and tests will be needed, which will prolong the melting.

5.4.4 Further comments on planning

Whatever the aim of the simulation is, there is a great need for close contact with specialists in areas such as metal, sand, fettling and logistics. All changes made in foundries' production will have an impact on the processes to a greater extent than many other manufacturing disciplines, which is not necessarily negative. A plan that is more electricity efficient may also be better from the point of view of productivity and quality. If, for example, the use of a resource is evened out, it may affect the wear on that machine in a positive way.

5.5 The role of the product and product mix in energy use

The flow of products obviously has a great impact on the production system in which they are produced or handled in some way. It is important not to disregard this effect; especially since much production planning is done based on the variety of products.

The focus of the methodology presented in this research study is based on the production flow of which the product is an integral part. The energy that is used is always connected to the resources and never to the product that used the resources. Since all energy use is analysed from the resource point of view, all data is presented in that way as well. However, it could be possible to model the product as an energy user instead, which would demand another approach to modelling which is not considered here.

The products, however, have a great impact on how the different resources react. Different products have different cycle times, will cause variations in power levels and other system parameters, such as increased or decreased need for heating and cooling, ventilation etc.

5.6 Summary of methodology for energy management using simulation

This chapter has presented a methodology for modelling and simulation of electricity use, how the methodology fits into the overall energy efficiency work and what information is needed to perform these kinds of simulations. The main parts of the methodology deals with input data, categorisation of data, conceptual modelling, model translation and experimentation.

As in most simulation projects the input data is of great importance. However, the structure of the data and the lack of detail in the input data will create problems for the modeller. The level of detail and how the data is measured may differ between energy data and corresponding production data.

Four different categories that processes can be divided into are defined. These categories are depending on behaviour of the process. States are used in the simulation model to represent the behaviour of the processes. How data can be handled in the model, how states are used for this and how output data can be represented is explained. There might be variations between simulation programs on how modelling can be performed.

Models that are built using the methodology proposed can make analyses within operational, tactical and strategic planning. However, there will be certain differences in the way the model is built. Compared to other simulation and optimisation techniques the described type of simulation model can show variations over time and in detail how resources interact with each other in the production and what it corresponds to in electricity use. Simulation based optimisation can therefore generate a more detailed description on the optimised system in comparison to for example the common MILP energy optimisation techniques.

Using simulation for analysing electricity usage will help companies cope with fluctuations in the production system, help them decrease electricity use and lower power load subscriptions which will increase their positions on the local, national, European and global markets.

6 Industrial case studies

This chapter presents four case studies that have been carried out during the course of this research. The case studies serve as a test bed for the methodology formulated and play an important role in validating the approach.

Use of case studies dictates a need to establish:

- How the cases selected are representative of the research challenge
- How many case studies are to be carried out
- The purpose of each of the case studies

With reference to the research question it was determined that industrial manufacturing facilities should be used as the case material and that the companies should be representative of the foundry industry. It was also decided to use multiple case studies due to the complexity of the problem such that each case study would address particular issues of interest.

When selecting companies the foundry industry was categorised into two parts: sand foundries and die casting plants. From this categorisation it was decided that the focus ought to be on sand foundries due to the high energy use among these companies compared to die casting plants. This reasoning is based on the fact that sand foundries often handle iron and steel, which demand more energy to melt than aluminium, magnesium and other non-ferrous metals, which are the main materials used in die casting. Additionally, sand casting often produces larger products, which requires more metal per product. Due to these circumstances, the energy cost of sand cast products make up a higher percentage of the total production cost compared to die cast products.

The companies were chosen partially based on the size of the foundry, the size of the castings produced and the metal used. Due to the fact that there are very few foundries in Sweden that are considered large, the foundries selected were one small (less than 50 employees) and three medium-sized foundries (between 50 and 250 employees). The medium-sized foundries, however, vary within this interval. The size of the castings varies from small (less than a kilogram) to large (hundreds of kilograms). The metals used in these foundries are iron (three foundries) and steel (one foundry).

The design of each case study varied. The focus of each case study was informed by the complexity of the manufacturing and the level of detail of the electricity data available.

In the four companies studied the knowledge of use of both simulation and energy efficiency work varied considerably. There was one company that had worked with energy efficiency intensively for a long time using advanced data collection, monitoring and control and with a well structured approach to investing in energy efficient equipment. Another company had also worked with energy efficiency for a long time but with less data monitoring and control. One company had used simulation for a period with good results. In general, people had more knowledge about energy use than about the use of simulation.

In the case studies presented in this research, two different simulation programs were used. These were AutoMod from BrooksSoftware [2007] and ED from Incontrol Enterprise Dynamics [Incontrol 2007]. Both programs have 3D capabilities and each has its own built-in programming language. In AutoMod, communication with MS Excel was via text files. ED has built-in possibilities to communicate with other programs such as the MS Office programs, which were used. These two programs are not chosen for any particular purpose, the methodology described and the work undertaken is independent of the simulation program used.

6.1 Overview of the case studies

Four case studies have been carried out, each with different goals (see Table 6). The objectives of each case study were informed by the complexity of the production system, the access and availability of production and electricity data, the problems related to the plant and the time frame available.

Input data to each of the case studies are shown in tables, which show which processes are included in the model and the corresponding electricity data. It should be noted that some of the data is slightly modified due to confidentiality.

It should be noted that all simulation models are built individually and for the purpose of this research. All processes are programmed to behave the way they behave in reality, using the built in programming languages of the programs used. Not all information behind every model is shown due to the vast amount of programming code used. Only the information vital for describing the use of the methodology proposed is presented. To give the reader extra information an appendix (Appendix A) is added where additional information about one of the case studies is presented. The information in this appendix gives the reader more detailed information surrounding the problems dealt with in that case study.

Table 6. Companies selected for case studies.

	ITT Flygt AB	AB Bruzaholms Bruk	SKF Mekan AB	Sandvik AB
Business area	Iron foundry	Iron foundry	Iron foundry	Steel foundry
Size	Medium	Small	Medium	Medium
Size of castings	< 160 kg	< 50 kg auto < 1,500 kg hand	< 700 kg	100 < 11,000 kg
Annual production	10,000 tonnes	2,000 tonnes	22,000 tonnes	10,000 tonnes
Simulation program used	ED	AutoMod	AutoMod	AutoMod
Physical area of simulation	Foundry	Entire plant	Furnaces and moulding	Foundry
Number of processes in simulation	16	16	10	6/86*
Objective	Reduction of electricity use and peak power loads.	Reducing peak power loads.	Co-operation between resources for reduction of electricity use.	Reduction of electricity use.
Energy audits and analysis	Data collected continuously and special data collected for simulation.	Overall energy audit conducted in 2004.	Energy audit conducted in 2003. Additional data collected for simulation.	Data collected for simulation.

* There are 6 different types of processes but with maximum use of the available mould box places that use vacuum, there are 86 different processes.

6.2 *Case study 1 – Medium-sized iron foundry (ITT Flygt AB)*

ITT Flygt is a medium-sized foundry with approximately 110 employees and produces 10,000 tonnes of iron castings annually. The foundry process is concentrated to one moulding line and a smaller shell moulding facility. There are three furnaces, of which two are used continuously and the third when needed. The plant, of which the foundry is a small part, has approximately 1,100 employees. The foundry is situated in a separate building together with some minor side operations such as painting. Finished goods are produced in other buildings close to the foundry building. The whole foundry building is modelled but not the rest of the plant. The focus was on electricity use. For heating, numerous sources of energy are used at the plant. These sources and their efficiency were not analysed in this case study.

6.2.1 Case study objective

The first objective of this case study was to determine if the substantial amount of data that is collected at the plant continuously, is sufficient for operational analysis of how the plant is run from an electricity efficiency perspective.

The second objective was to identify if the plant is run in the most efficient way and to find possible improvements in the way the company works in terms of electricity use.

6.2.2 Production and energy parameters

ITT Flygt has a track record of energy efficiency work and is considered a pioneer in the Swedish foundry industry. The company has a well-defined energy and environmental policy and has a long history of measurement and improvement work. They have a well defined and extensive manufacturing supervision and control system which was used to draw electricity data from. Additional data was measured specifically for the purpose of simulation studies. All data was analysed, categorized and stored in MS Excel. The program ExpertFit [2007] was used to fit a distribution to the data. The electricity data used in the model is shown in Table 7. Melting is missing in the table since melting is handled separately as a category 4 process and can not be represented by a stochastic behaviour. It has five different states of which the two most common states are maximum power melting which uses 5 MW and holding which uses 0.15 MW.

Table 7. Electricity input data used in the simulation model of ITT Flygt AB.

Process	State	Distribution	Parameter 1	Parameter 2
Moulding	Working	weibull	207.0	7.6
	Idle	lognormal	59.9	0.2
	Off	gamma	9.0	2.1
Sand Preparation and mixer	Working	weibull	231.1	10.5
	Idle	weibull	16.5	12.5
	Off	uniform	0	0
Micro	Working	weibull	101.2	11.3
	Idle	weibull	22.7	3.8
	Off	uniform	0	0
Shot blasting	Working	log-logistic	150.3	99.0
	Idle	uniform	0	0
	Off	uniform	0	0
L20 + L40	Working	log-logistic	26.6	12.1
	Idle	log-logistic	3.1	11.5
	Off	log-logistic	3.1	11.5
LFB25+LFB50	Working	pearson type V	218.6	12.7
	Idle	log-logistic	1.1	8.7
	Off	uniform	1	1
Painting	Working	uniform	151.0	206.1
	Idle	uniform	1	2
	Off	uniform	1	2
Sand preparation conveyor	Working	lognormal	97.1	0.053
	Idle	log-logistic	36.7	36.8
	Off	uniform	1	1
Vibrodrum	Working	weibull	59.2	14.0
	Idle	log-logistic	24.6	30.9
	Off	log-logistic	8.6	0.018
Fettling	Working	log-logistic	13.4	38.2
	Idle	uniform	0	0
	Off	uniform	0	0
Filter fettling	Working	weibull	67.1	6.6
	Idle	uniform	0	0
	Off	uniform	0	0
Filter sand preparation	Working	weibull	146.5	70.4
	Idle	uniform	0	0
	Off	uniform	0	0
Filter melting	Working	log-logistic	59.5	11.0
	Idle	uniform	0	0
	Off	uniform	0	0

The processes that are modelled stands for 75-80 percent of the total electricity use in the foundry. Most support processes are not included which stands for the rest together with some small production processes that are only used during shorter periods. Additional information about the electricity system was given by the energy expert at the maintenance department. Production data was also collected from the supervision system as well as from the business system. Most of the detailed scheduling information was given by the production planner and the foundry manager. Additional information was collected from other personnel involved. Order lists are based on historical production. Hence, the information was based on documentation, interviews and observations. Additional information concerning production and energy related data can be found in Appendix A.

6.2.3 The model

The focus when modelling this facility was on the moulding line, the furnaces and the product flow through the plant. A simple process flow of the production processes is shown in Figure 29 and the main parts of the model are shown in Figure 30. Support processes were modelled as passive elements, which mean that their use was varied stochastically according to category 1 or 2 in the methodology. Such variations were not dependent on other activities at the plant. The reason for this is the difficulty in linking the electricity use in a support process such as ventilation to the production processes it supports. The air flow of the system is too irregular and complex to be analysed in this type of simulation model. Most production processes fit into category 1, except for melting in electrical furnaces which belong to category 4. Also the holding furnace, used when pouring metal into the moulds, belongs to category 4. However this furnace runs on LPG. The energy use of the furnace is modelled but does not have effect on the total power load. The simulation model was built including all the electricity using resources in the foundry building. Heating with oil, district heating and renewable energy sources was not considered.

When calculating power loads a time step of 6 minutes was used as the shortest step for using only one distribution. Most simulation runs were also made with this short interval as the sampling interval since the interaction between the melting furnaces and the moulding and pouring was studied, which demands a relative short time span between samplings. Some overall studies were also made. In these a sampling interval of 30 minutes was used which is enough to get a good picture of the results without sampling to much data.

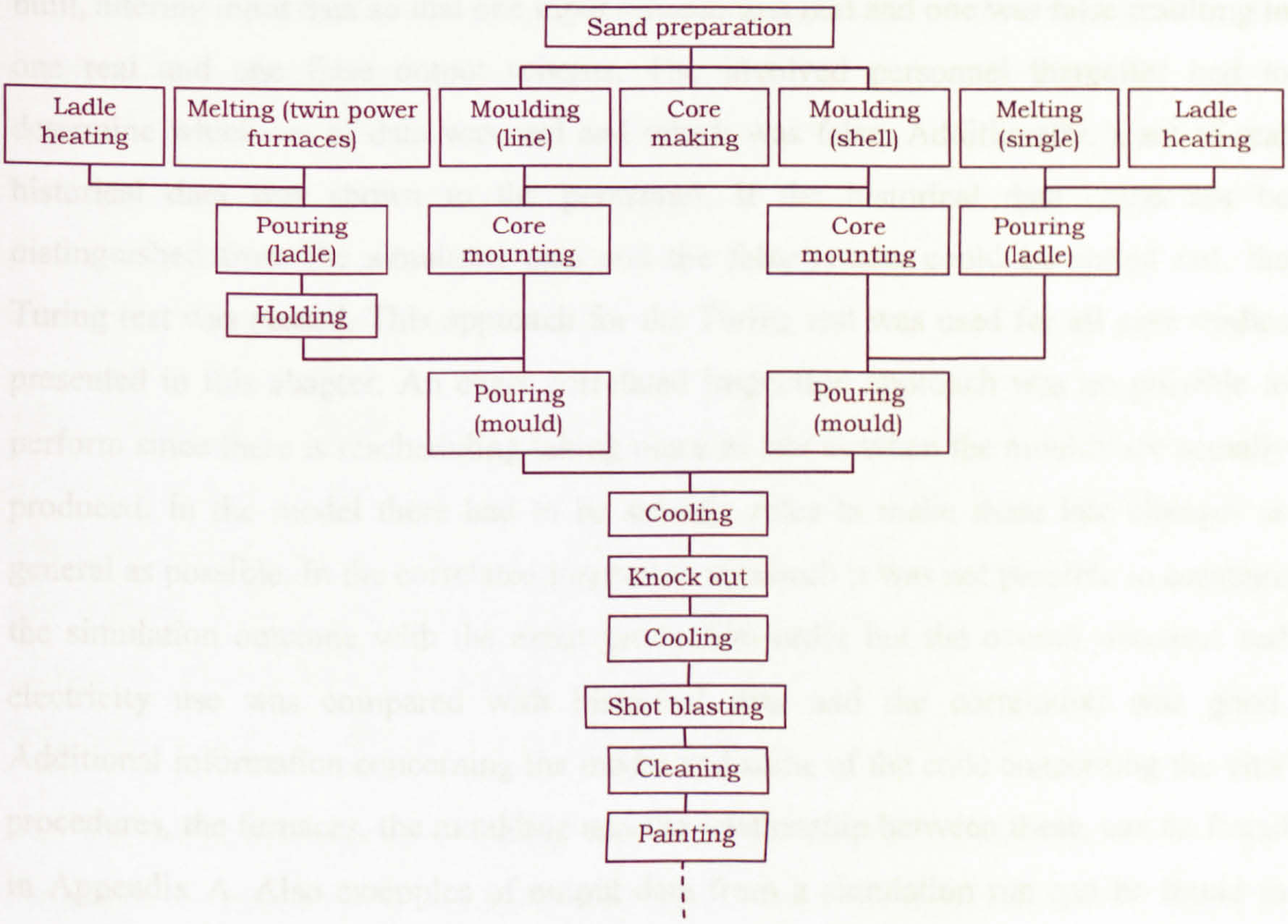


Figure 29.Main foundry processes at ITT Flygt AB.

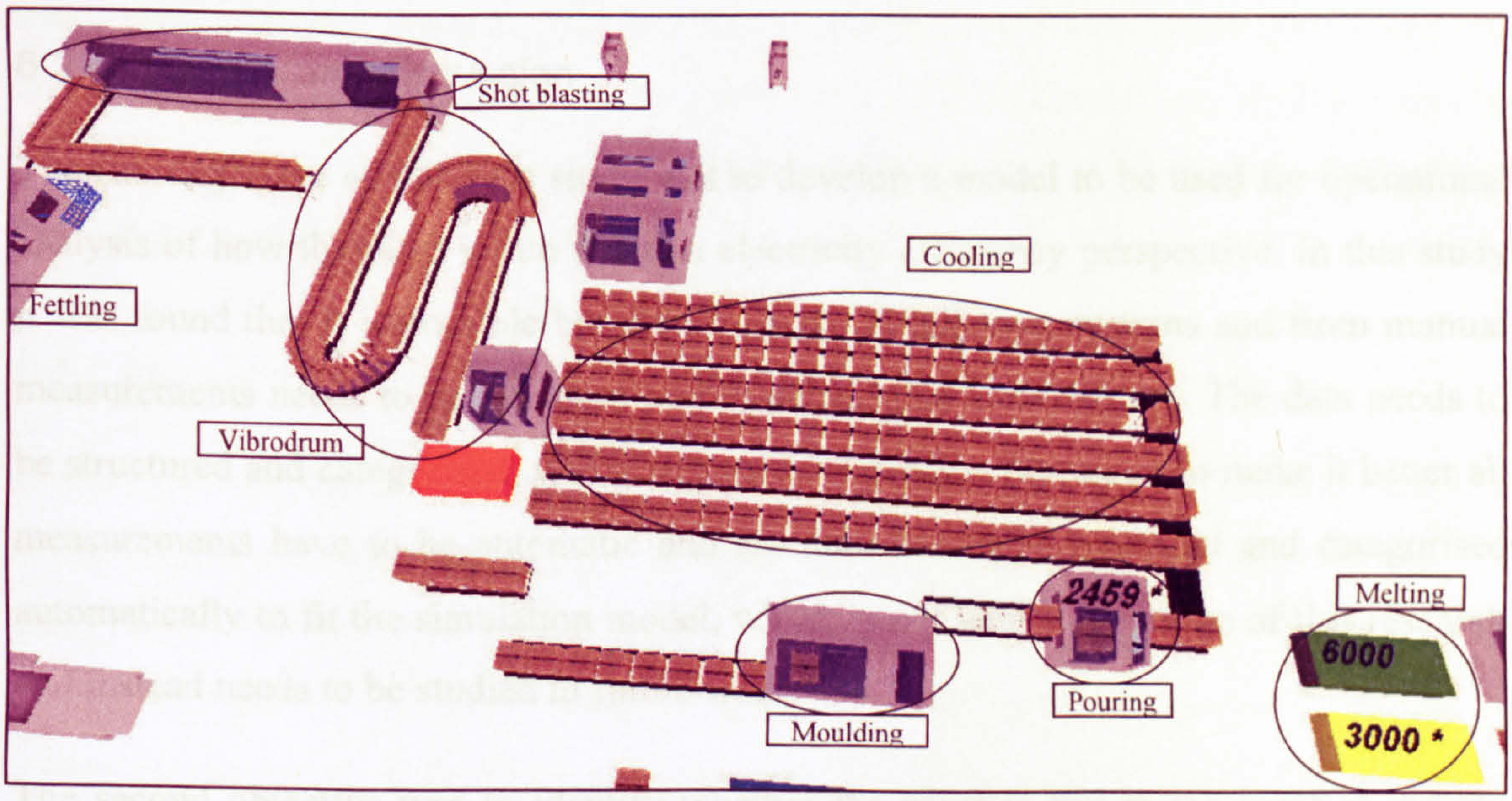


Figure 30.The central parts of the simulation model of ITT Flygt AB.

The model was validated mainly using Turing test and the correlated inspection approach but also using animation. The Turing test was performed using the model built, altering input data so that one input scheme was real and one was false resulting in one real and one false output scheme. The involved personnel thereafter had to determine which set of data was real and which was false. Additionally, a set of real historical data was shown to the personnel. If the historical data could not be distinguished from the simulated data and the false results could be sorted out, the Turing test was passed. This approach for the Turing test was used for all case studies presented in this chapter. An exact correlated inspection approach was no possible to perform since there is rescheduling taking place as late as when the moulds are actually produced. In the model there had to be specific rules to make these late changes as general as possible. In the correlated inspection approach it was not possible to compare the simulation outcome with the exact production order but the overall outcome and electricity use was compared with historical data and the correlation was good. Additional information concerning the model and some of the code concerning the vital procedures, the furnaces, the moulding and the relationship between these, can be found in Appendix A. Also examples of output data from a simulation run can be found in Appendix A.

6.2.4 Results and discussion

The first objective of this case study was to develop a model to be used for operational analysis of how the plant is run from an electricity efficiency perspective. In this study it was found that it is possible but data from the monitoring systems and from manual measurements needs to be managed before being used in the model. The data needs to be structured and categorised, which was made manually. However, to make it better all measurements have to be automatic and the data has to be managed and categorised automatically to fit the simulation model, which is not within the scope of this research and instead needs to be studied in future work.

The second objective was to identify whether the plant is run in the most electricity efficient way and if not, to find possible improvements. The moulding, core mounting, pouring, initial cooling, knockout and mould changing work together in a line and are therefore fairly sensitive to interruptions. Only very small buffers can be built at specific places, such as in front of the pouring station where less than a handful of moulds can wait. Analyses made of historical data from the furnaces showed that the furnaces were occasionally in holding state for a long time. This mainly happened when problems had occurred somewhere in the line but also at times when the melting was working too fast for the line. Reasons for the furnaces working too fast could for example be that smaller parts were produced and less molten iron was needed. The times when the line had to wait for the furnaces were few.

Two alternative solutions for improvements were proposed and modelled. The first scenario was to simulate an increase of the information flow from the moulding process, letting the melting know earlier how much iron is needed and information about when a new furnace has to be started to be able to be ready in time. The second scenario was to change the availability of the moulding line to see how this affects the holding times, both with the original settings and with the first proposed improvements made.

The first scenario shows that holding times can be decreased from 58 percent to 21 percent of the total time during active production which is a decrease by 64 percent. A certain amount of holding is always necessary due to testing times and the pouring time when emptying the furnace. The second scenario shows that when availability is increased on the moulding line the output increases. The planner can use the model to visualise this and to analyse how much electricity and money an increase in availability by a certain percentage is equivalent to.

6.3 Case study 2 – Small iron foundry (AB Bruzaholms Bruk)

Bruzaholms Bruk is a small foundry with approximately 40 employees and produces approximately 2,000 tonnes of iron castings annually. The foundry process is concentrated to one moulding line and two furnaces, of which one furnace is in operation most of the time. Only occasionally are both in operation, which is interesting, however, with regard to power use. The two occasions where both furnaces are used simultaneously are:

- The most frequently used furnace is rebuilt and sintered every ten days. The sintering is a process where the rebuilt furnace is subjected to a progressive load during a period of approximately 8 hours. This process is needed to get the best performance from the furnace. During the sintering the second furnace is used for melting. The process of sintering is normally started early in the morning. After the furnace is up and running again around lunchtime both furnaces are used during the rest of the day.

- On some days both furnaces are used at the same time. This happens only rarely but can occur if it is difficult to get a good mix between alloys in one furnace or when there is a great need for metal from the smaller hand moulding department.

The working hours of the plant are extended dayshifts. The people in the melting facility start earlier to be able to deliver the first batch when the moulding starts.

6.3.1 Case study objective

The main objective of this study was to reduce the maximum total power load of the plant through improved planning of activities.

6.3.2 Production and energy parameters

An energy audit had taken place at the end of 2004 [Karlsson 2004]. Information from this audit has been used as input to the simulation model. Since the time when the energy audit took place an extension to the cooling lane has been built with the aim of achieving a lower temperature of the goods before the knockout. The new lane does not affect the electricity use by a significant amount but has been included in the simulation model. Otherwise there were no differences between the status of the plant while doing the energy audit and while carrying out this case study. The historical electricity use for all resources was categorised, and stored in MS Excel together with prices and taxes. Main electricity data used is shown in Table 8. All electricity using processes are included in the model which means that the power load also can be analysed.

The main parts of the production related information used when building the simulation model, as well as the electricity related information, are based on documentation, interviews and observations. Most of the detailed scheduling information was given by the production planner. Additional information was collected from other personnel. Order lists are based on historical production.

Table 8. Electricity input data used in the simulation model of AB Bruzaholms Bruk.

Process	Working (kW)	Idling (kW)	Off (kW)
Melting	1200	120	0
Moulding	75	40	2
Sand Preparation	77	42	5
Knockout	17	9	0
Shot blasting	71	43	1
Fettling	5	2	0
Core making	12	4	1
Elevators	40	3	0
Ventilation	125	10	5
Heating	20	3	3
Lighting	52	7	1
Compressed air	65	5	1
Cooling (summer only)	5	1	1
Transformers	18	18	18
Pumps	13	8	2

6.3.3 The model

The modelled system consists of all production processes as well as support processes. The main production processes are one moulding machine, two furnaces, a sand mixer, conveyor belts, knockout, shot blasting and fettling stations. The main process flow is shown in Figure 31. Support processes are for example ventilation, heating, lighting and compressed air. An overview of the simulated system is shown in Figure 32.

The simulation model was built including all the electricity using processes. Liquefied Petroleum Gas (LPG) for ladle heating was included but had no significant impact on the overall system. Heating with oil and renewable energy sources was not considered.

The input data, collected from the energy audit report, was relatively limited and there was no possibility to manually measure electricity data. The results can not be more detailed than the input data so it was determined that the level of detail produced would not be as comprehensive as first forecast. All processes were handled as category 1 processes except for the melting, which started as a category 1 but when adding more states, as described below, it turned into a category 4. In the model as well as in reality the moulding sets the speed of the line. However, the furnaces can be a bottleneck if not delivering iron in an even pace. Also the knockout can occasionally be a bottleneck.

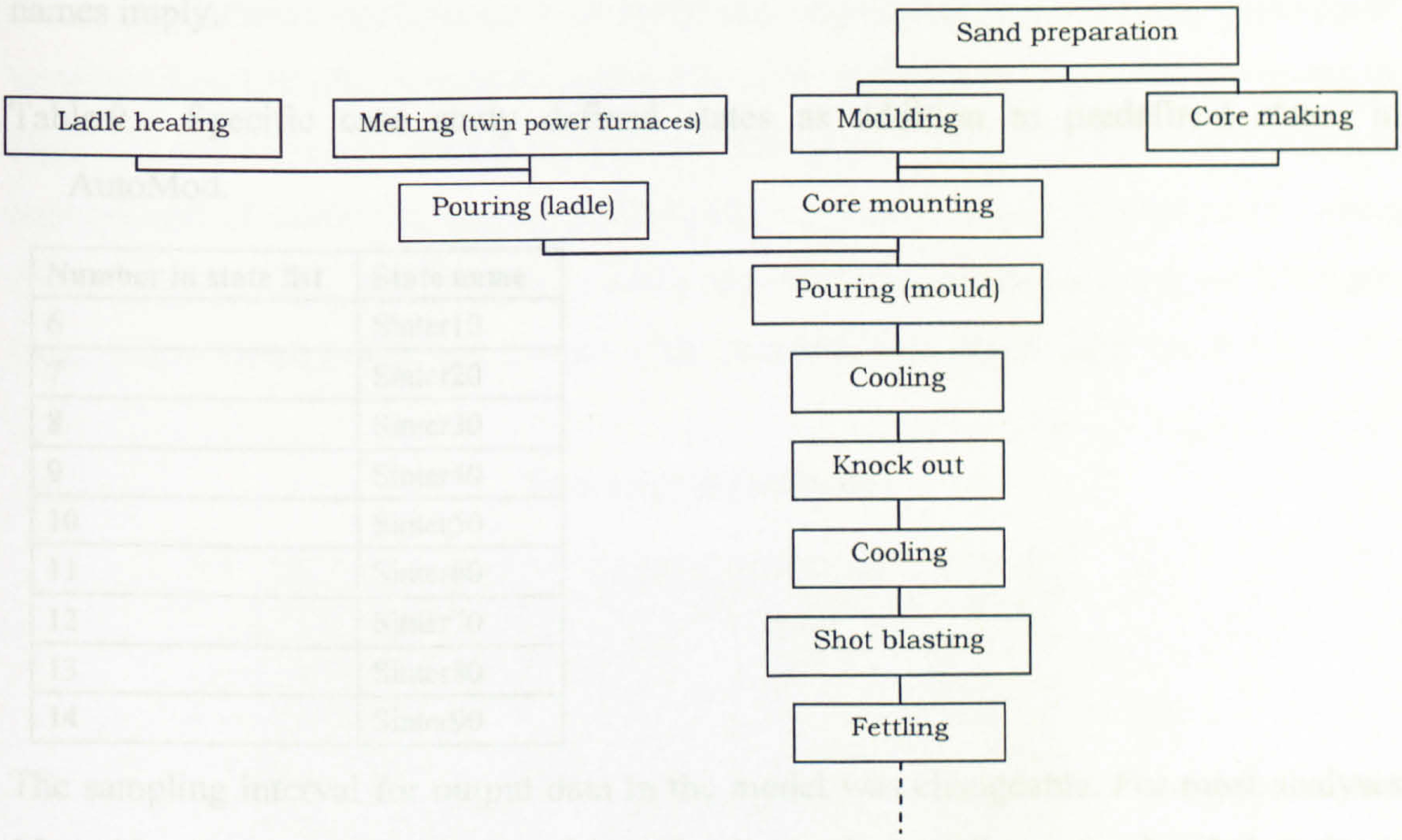


Figure 31.Main foundry processes at AB Bruzaholms Bruk.

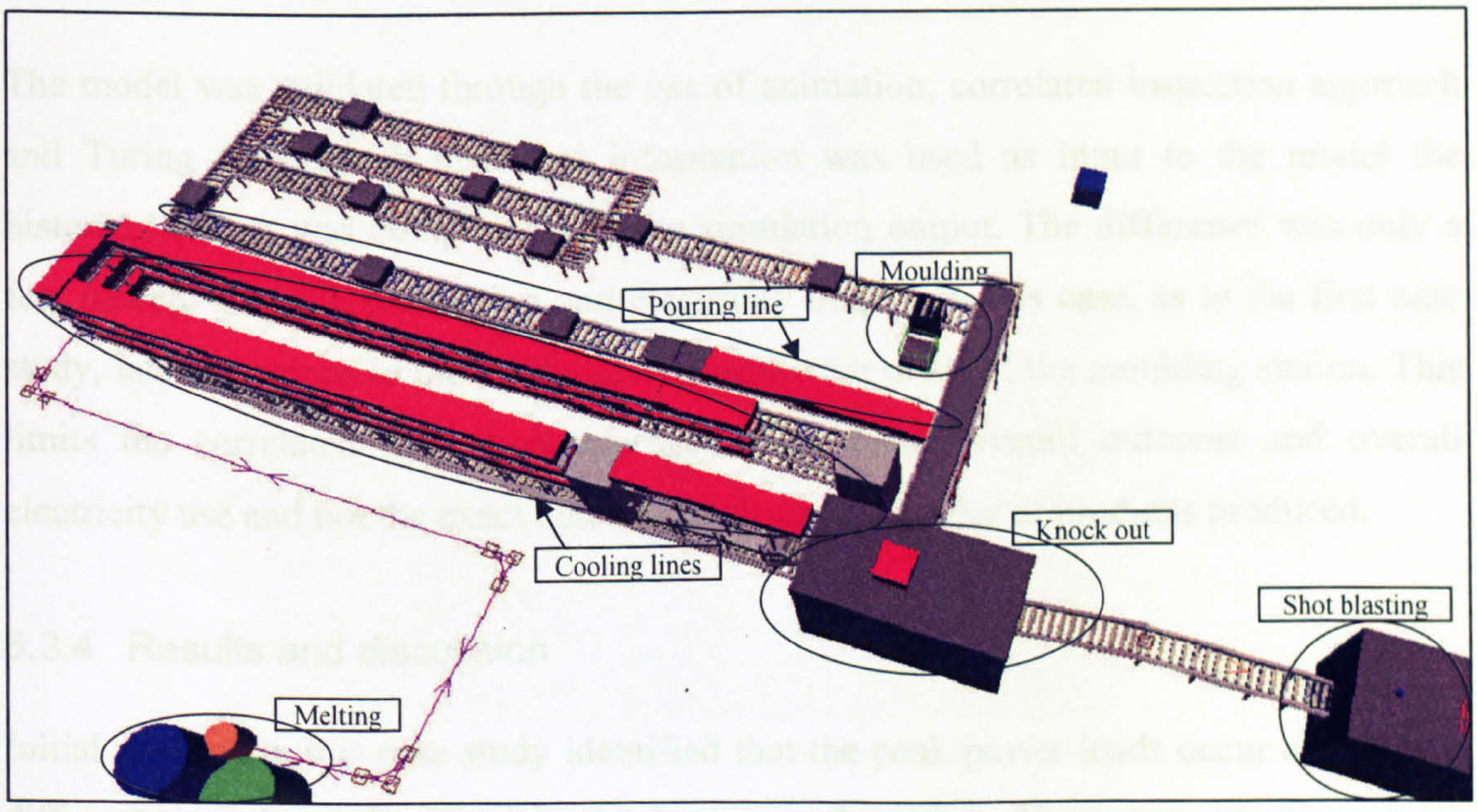


Figure 32.The central parts of the simulation model of AB Bruzaholms Bruk.

Since all electricity using processes were analysed, less common events such as sintering was also modelled. This meant that additional states had to be added to represent the sintering stages. During sintering a ramp up of the power use was done. Therefore nine additional states were added, as shown in Table 9, so that the ramp up could be modelled. These different stages use a percentage of the working load as the names imply.

Table 9. Specific case study defined states as addition to predefined states in AutoMod.

Number in state list	State name
6	Sinter10
7	Sinter20
8	Sinter30
9	Sinter40
10	Sinter50
11	Sinter60
12	Sinter70
13	Sinter80
14	Sinter90

The sampling interval for output data in the model was changeable. For most analyses 15 or 30 minutes was used to avoid storing to much data. For more detailed analyses concerning critical situations one minute was used.

The model was validated through the use of animation, correlated inspection approach and Turing tests. Since historical information was used as input to the model the historical output was compared with the simulation output. The difference was only a few percent for both production and electricity output. In this case, as in the first case study, late alterations to the production schedule are made at the moulding station. This limits the correlated inspection approach to compare overall outcome and overall electricity use and not the exact outcome such as exact order of products produced.

6.3.4 Results and discussion

Initial analysis in this case study identified that the peak power loads occur during two different periods as described in the background section. These two situations were simulated and analysed and the results were validated by the production manager. Two alternative solutions for planning the sintering processes were discussed and these were simulated. The first alternative is to sinter during the night which eliminates the need to use the two furnaces at the same time. The other alternative is simply to stop using the second furnace when the first has been sintered and is ready to use. This however is considered to be a waste since there already is a large amount of energy stored in the furnace. Simulation experiments were made showing that the levels of peak loads could be reduced by 130 kW, or approximately 8 percent. Before and after charts are shown in Figure 33 and Figure 34. This peak reduction means not only a cost reduction but also a reduced risk of exceeding current subscription levels and also a possibility to reduce subscription levels in the future. The extra cost, however, of having a person doing the work during the night will offset some of the financial benefits of the solution.

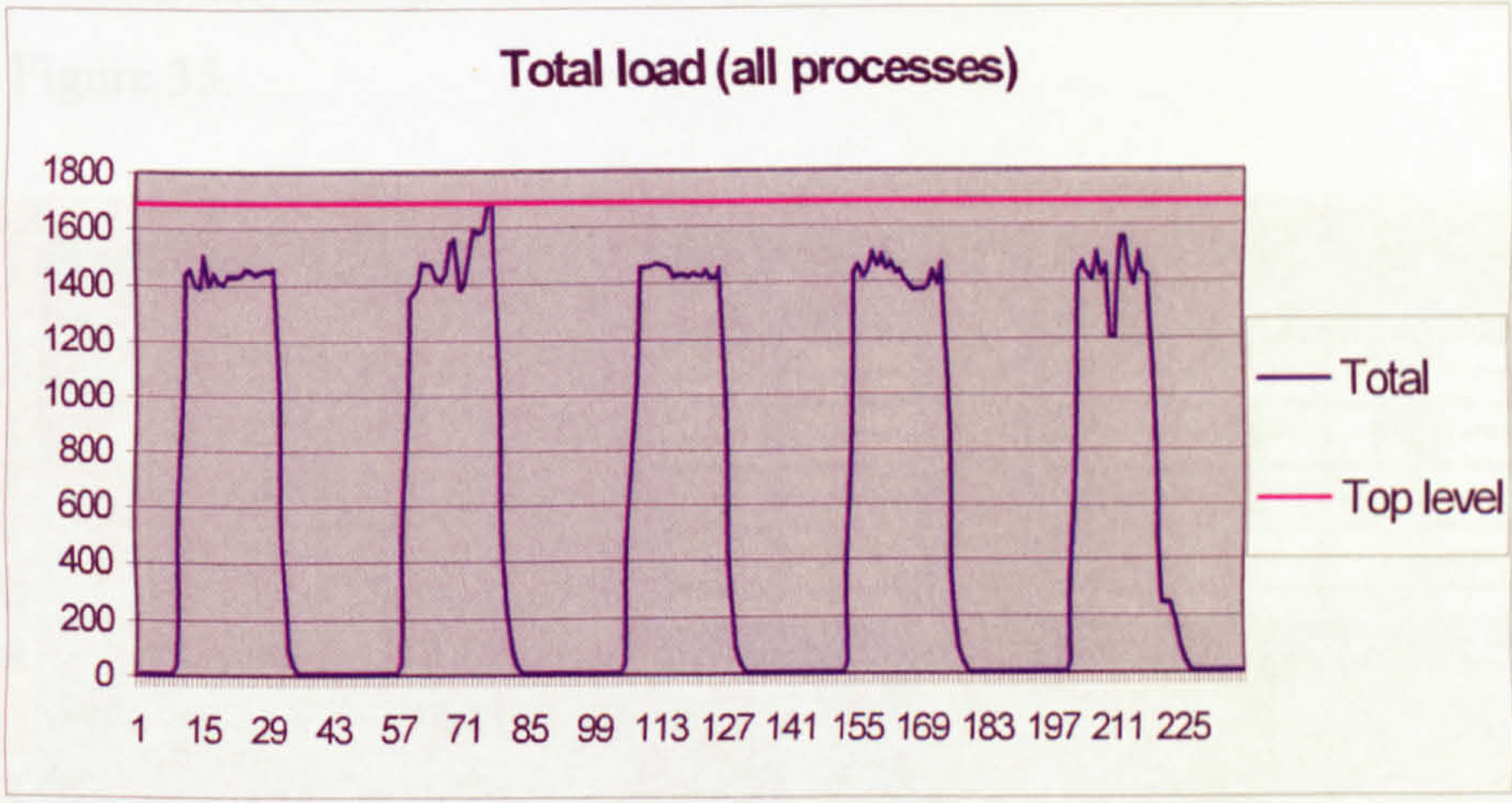


Figure 33.Power load when sintering parallel to melting.

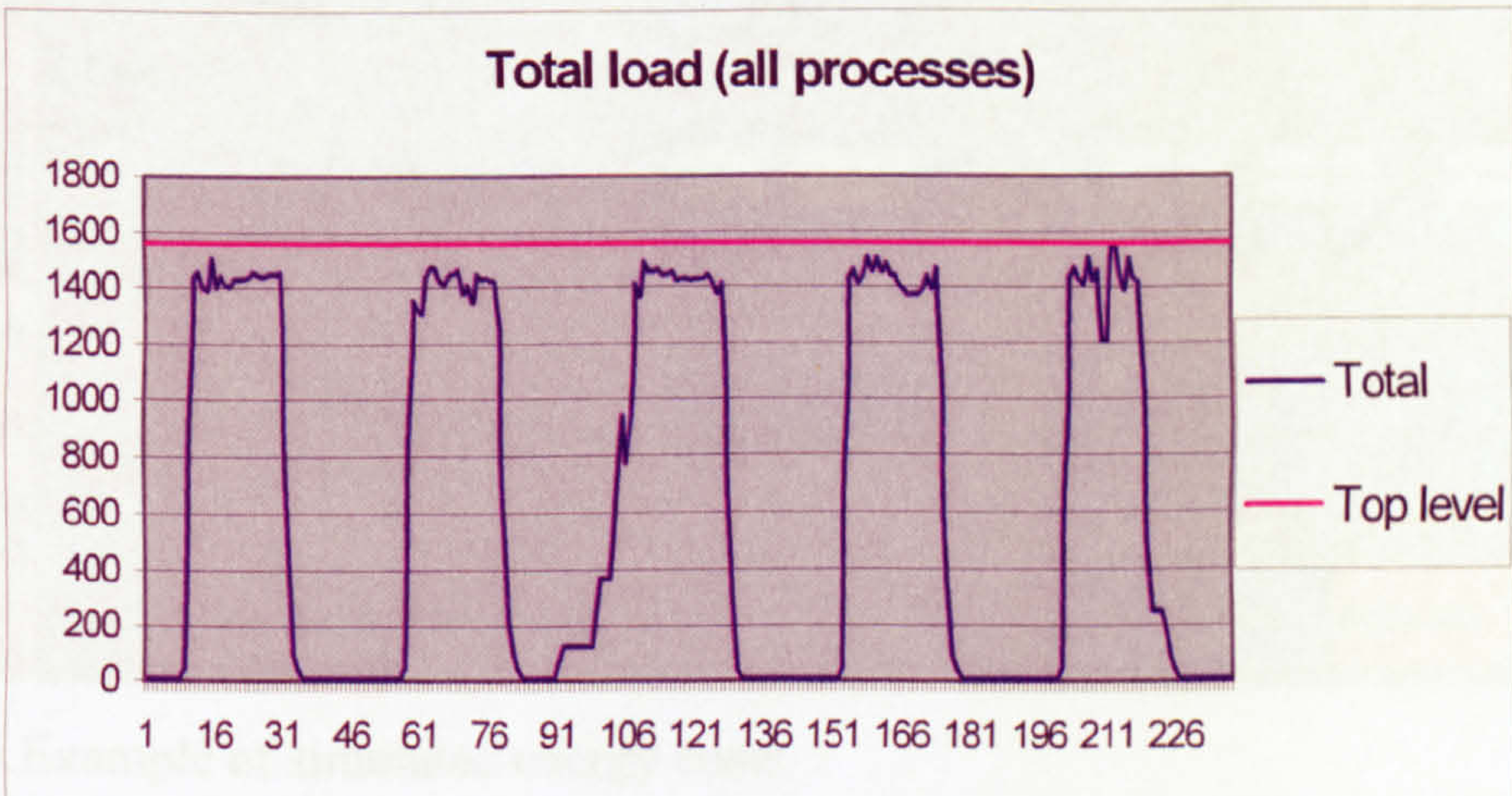


Figure 34.Power load when sintering during off-hours.

A parameter often used as a KPI in the foundry industry is the amount of electricity used to produce one tonne of good castings, usually presented in MWh/tonne. Since the company wanted to extend working hours from an extended dayshift to two shifts it was interesting to see how this affects electricity use. This type of KPI is most useful for making comparisons between different periods for the foundry itself. Comparing the KPI with other foundries does not always show how well the foundry performs, due to the varying types of production systems that the foundries have. But with a careful approach it can serve as an indicator for benchmarking [Thollander et al. 2005]. Extending the working hours logically has a "positive" impact on the electricity use since it does not increase as much as the output. Simulations showed an increase in production output by 67 percent, an increase in total electricity use by 39 percent and a decrease in electricity use per tonne by 16 percent. Results from one of the runs are shown in Figure 35.

	Energy Use	Cost		
Production processes				
Unit: kr	(MWh/year)	Per day	Per week	Per year (47 w)
Melting	2 108	3 588	17 941	843 243
Ladle heating	0	0	0	0
Sand preparation	140	200	1 000	47 000
Molding	167	288	1 442	67 786
Knock Out	27	47	234	11 013
Shot peeling	119	202	1 009	47 443
Fettling	6	11	53	2 500
Core making	37	64	318	14 927
Elevators	4	6	30	1 410
TOTAL	2 609	4 406	22 028	1 035 322
Supporting processes				
Unit: kr	(MWh/year)	Per day	Per week	Per year (47 w)
Ventilation	288	491	2 455	115 406
Heating	64	109	546	25 646
Lighting	128	218	1 091	51 291
Compressed air	160	273	1 364	64 114
Cooling	0	0	0	0
TOTAL	640	1 091	5 457	256 457
Other				
Unit: kr	(MWh/year)	Per day	Per week	Per year (47 w)
Transformers	40	68	341	16 029
Pumps	32	55	273	12 823
TOTAL	72	123	614	28 851
TOTAL, ALL PROCESSES	3 321	5 620	28 099	1 320 630
SUBSCRIPTION		3 002	15 011	780 566
TOTAL, SUBSCRIPTION INCLUDED		8 622	43 109	2 026 142

Figure 35.Example of simulated energy costs.

It was found that it was not possible to make a more detailed analysis due to the lack of detailed input data. It was also difficult to make accurate production plans due to the lack of detail in planning procedures and the high dependency on manual decisions on the shop floor.

6.4 *Case study 3 – Medium-sized iron foundry (SKF Mekan AB)*

SKF Mekan, situated close to the central area of the city of Katrineholm, has in recent years worked progressively with environmental issues, of which energy use is one part. Noise and pollution are other important environmental issues for SKF Mekan. SKF Mekan is a medium-sized foundry with 120 employees and produces 22,000 tonnes of iron castings annually. The plant in Katrineholm also does some grinding and finishing. The production process consists of five melting furnaces, two holding furnaces and two different moulding lines: a vertical moulding line called the Disa line and a horizontal moulding line called FA68.

6.4.1 Case study objective

The objective was to analyse how the production planning of the foundry can affect its productivity and electricity use. The intention was to evaluate different alternatives in planning strategies with the help of the simulation model. By making alterations to the way production is run the aim was to see if it would be possible to plan the melting, holding, moulding and their interactions better to reduce holding losses due to gaps between melting and moulding.

The company was also in the process of investing in new furnaces. Therefore this case study was used to analyse the capacity of the furnaces compared to the capacity of the moulding line. After that alterations were made to the model according to the planned investments with the aim to see what impact this investment decision would have on the production and electricity systems.

6.4.2 Production and energy parameters

An extensive energy audit was conducted in 2003 [LiU 2003a] [LiU 2003b]. Additional measurements were made during the project to add to the data in the energy audit reports and to update older figures.

Production parameters were gathered from the business systems and from the production personnel, who described the complex planning of furnaces and alloys for the different castings in the different lines. Input and output data was handled in MS Excel. The electricity data used in the model is shown in Table 10.

Table 10. Electricity input data used in the simulation model of SKF Mekan AB.

Process (ITT)	Working	Idle	Off
LFD4 (melting furnace)	1700	175	0
LFD5 (melting furnace)	1700	175	0
HF1 (melting furnace)	2000	100	0
HF2 (melting furnace)	2000	100	0
HF3 (melting furnace)	2000	100	0
LFR1 (holding furnace)	220	50	0
LFR2 (holding furnace)	280	50	0
DISA (holding furnace)	160	30	0
DISA line (excl. furnace)	65	5	0
FA68 line	150	10	0

6.4.3 The model

Only the interaction between the most electricity intensive equipment, the furnaces and the moulding lines, was included in this model. The main process flow is shown in Figure 36 and an overview of furnaces and moulding machines in the simulation model are shown in Figure 37. The furnaces and the moulding machines alone use 55-60 percent of all the total electricity used in the foundry. Other production processes and support processes are not included in the model.

The logic which decides the interaction between different furnaces is complicated. All metal needs to be melted in the melting furnaces. Most of it is temporarily stored in the holding furnaces but some alloys goes directly to the moulding lines. The order lists, which decides what to be moulded in the moulding lines needs to be synchronised with the furnaces. Even with a complex logic it was possible to treat all processes as category 1 processes. No additional states were used. The model was built so that a sample of output data was gathered every 5 minutes. After the run it is then possible for the user to choose which interval to look at. This is also described in section 5.2.6 and in Figure 24 and Figure 25.

Most of the model outcome was validated mainly using the correlated inspection approach but also by using the degenerate tests, changing the demand for metal to look at how the simulated system handles these situations. Using animation and Turing test was also used to validate the model.

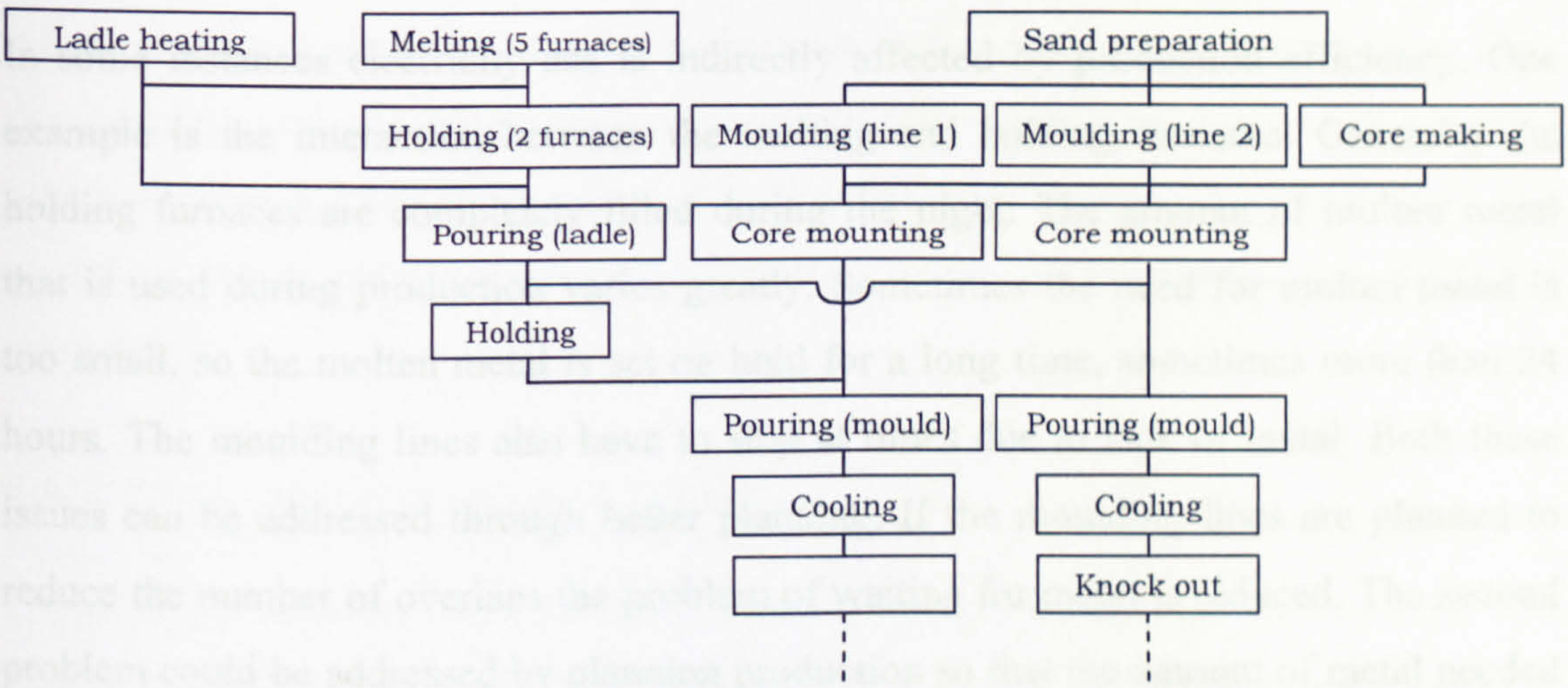


Figure 36.Main foundry processes at SKF Mekan AB.

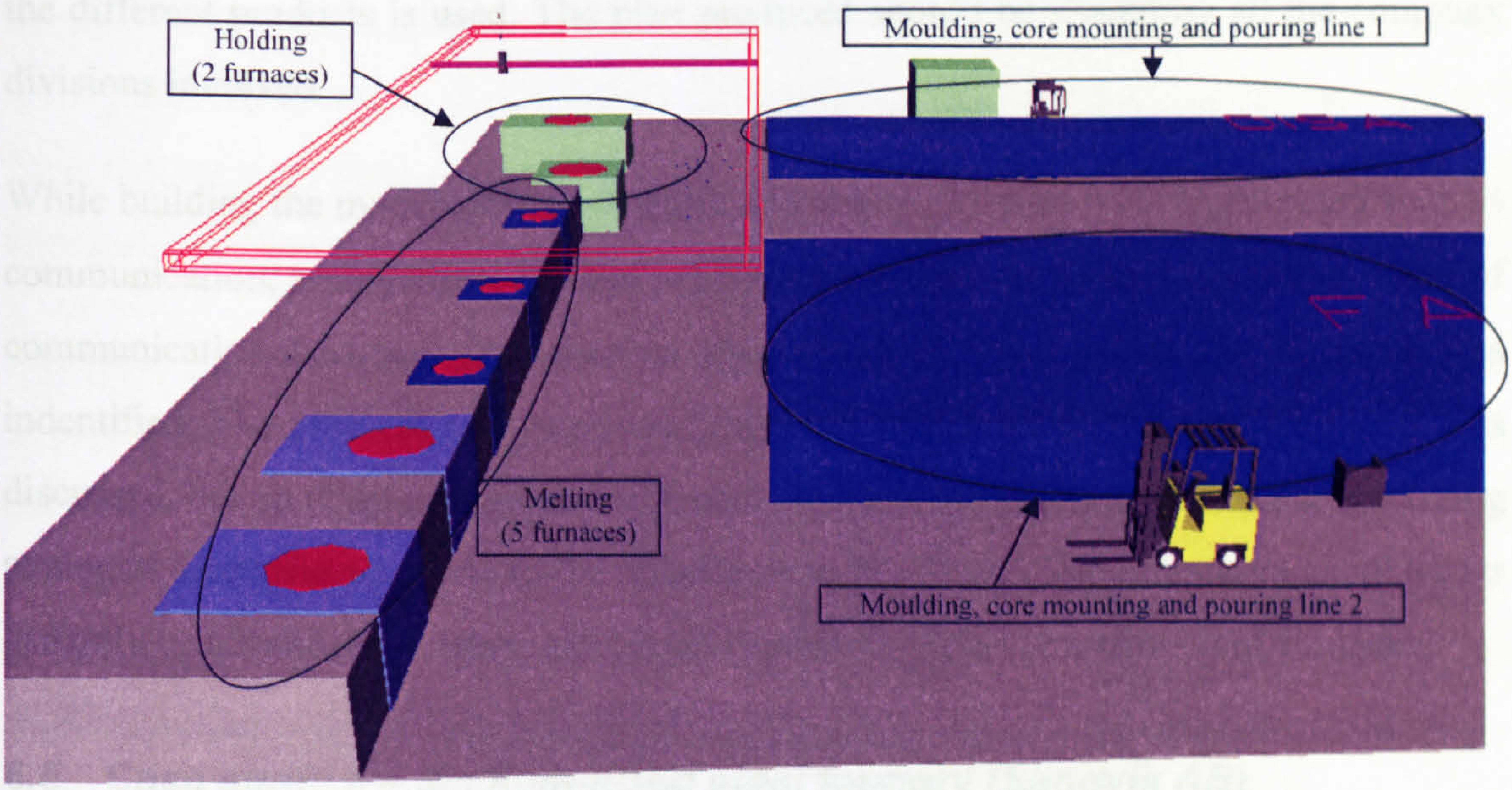


Figure 37.The central parts of the simulation model of SKF Mekan AB (furnaces and moulding lines).

6.4.4 Results and discussion

This case study showed how different production plans affect productivity and electricity use in the foundry. There is generally a connection between efficient production and efficient electricity use. One representative example is when two moulding lines request the same alloy from the same holding furnace at the same time. When this occurs, the production is inefficient and result in excessive electricity use.

In some instances electricity use is indirectly affected by production efficiency. One example is the interaction between the melting and holding furnaces. Generally the holding furnaces are completely filled during the night. The amount of molten metal that is used during production varies greatly. Sometimes the need for molten metal is too small, so the molten metal is set on hold for a long time, sometimes more than 24 hours. The moulding lines also have to stop at times due to lack of metal. Both these issues can be addressed through better planning. If the moulding lines are planned to reduce the number of overlaps the problem of waiting for metal is reduced. The second problem could be addressed by planning production so that the amount of metal needed during the day is controlled. The planning will be more predictable if historical data of the different products is used. The plan produced should be shared by all the company divisions involved.

While building the model several strategic and practical issues were highlighted such as communication, arrangement of work schedules and optimal furnace capacities. Lack of communication between personnel on the moulding lines and at the furnaces was indentified. The problem with non-matching work schedules on the moulding lines was discussed, but no simple solution was found. By highlighting the problem the marketing strategies were altered to adjust the imbalance in the future. The furnace capacity issues can only be solved if and when a decision is made to invest in a new set of furnaces.

6.5 Case study 4 – Medium-sized steel foundry (Sandvik AB)

Sandvik has the largest steel foundry in Sweden, producing some 10,000 tonnes annually. The foundry is situated in the south of Sweden and is the only Swedish foundry using large-scale vacuum moulding. Vacuum moulding means that the sand is held together with the help of vacuum instead of a chemical binder. Sandvik has previously worked with simulation and experience from that work was used during this case study.

6.5.1 Case study objective

The objective of this case study was to build a detailed production planning model. The model would be built to produce detailed schedules from a set of predefined rules. From the schedules the electricity system would be analysed to see how well the best schedules from a productivity point of view relate with regard to electricity use. The predefined rules were progressively adjusted, taking into account the electricity perspective.

6.5.2 Production and energy parameters

Production parameters were gathered from the company business system. Data was stored in MS Excel and MS Access. It was important to be able to easily import a preliminary schedule from the business system to the MS Excel sheet to minimise manual work. This was achieved by a thorough analysis of the data available in the system and the structure of the business system. Standardising the way data is exported from the business system made it easy to import data sets to the spreadsheet without additional manual work.

Available electricity data was withdrawn from the business system in the same manner as production related data. The data still missing was collected continuously throughout the work. The electricity data used in the model is shown in Table 11. The processes that are modelled stands for more than 80 percent of the total electricity use in the foundry. Most support processes are not included which stands for the rest together with some additional smaller production processes. In the table large and small boxes are presented as two processes. However there are 82 places that can be occupied by mould boxes and use vacuum so the number of actual processes is much larger.

Table 11. Electricity input data used in the simulation model of Sandvik AB.

Process	Working (kW)	Idling (kW)	Off (kW)
Melting	6000	200	0
Moulding VF01	300	60	0
Moulding VF02	250	50	0
Moulding VF03	200	45	0
Large box	5	0	0
Small box	3	0	0

6.5.3 The model

The model contains one furnace, three moulding lines and the hand moulding facility. All transport in the main building is undertaken using an overhead crane. The main process flow is shown in Figure 38 and the central parts of the simulation model are shown in Figure 39.

The vacuum system can only use a fixed amount of connections and there are a fixed number of places on which mould boxes can be placed. At the moment there are 82 different places of which 28 can be used to store big boxes and the rest to store small boxes. Since the planning algorithms bases decisions on current state in the model the model needs to be thoroughly initiated and updated with the current situation at the shop floor. This is visualised in MS Excel with a picture that shows which moulds that uses the vacuum spaces, see Figure 40. The start position is updated with data from the business system before every simulation run.

The planning algorithms are based on current planning rules in the plant. The generated plans consist of production sequences for orders to be produced in the melting facility as well as the moulding lines. After the knockout station there is a push flow all the way through the rest of the processes in the foundry.

In the model the furnace was treated as a category 4 process and the rest as category 4 processes. No additional states were needed in this case study. As in the previous case study, the sampling interval was 5 minutes and the user can chose what interval to look at after the run.

The model was validated using Turing tests, correlated inspection approach and animation. Since the model is the generator of schedules test were made were the outcome from the simulation model was compared with the actual outcome. At the same time this outcome was compared with the average outcome other test periods which is presented in the results section of this case study.

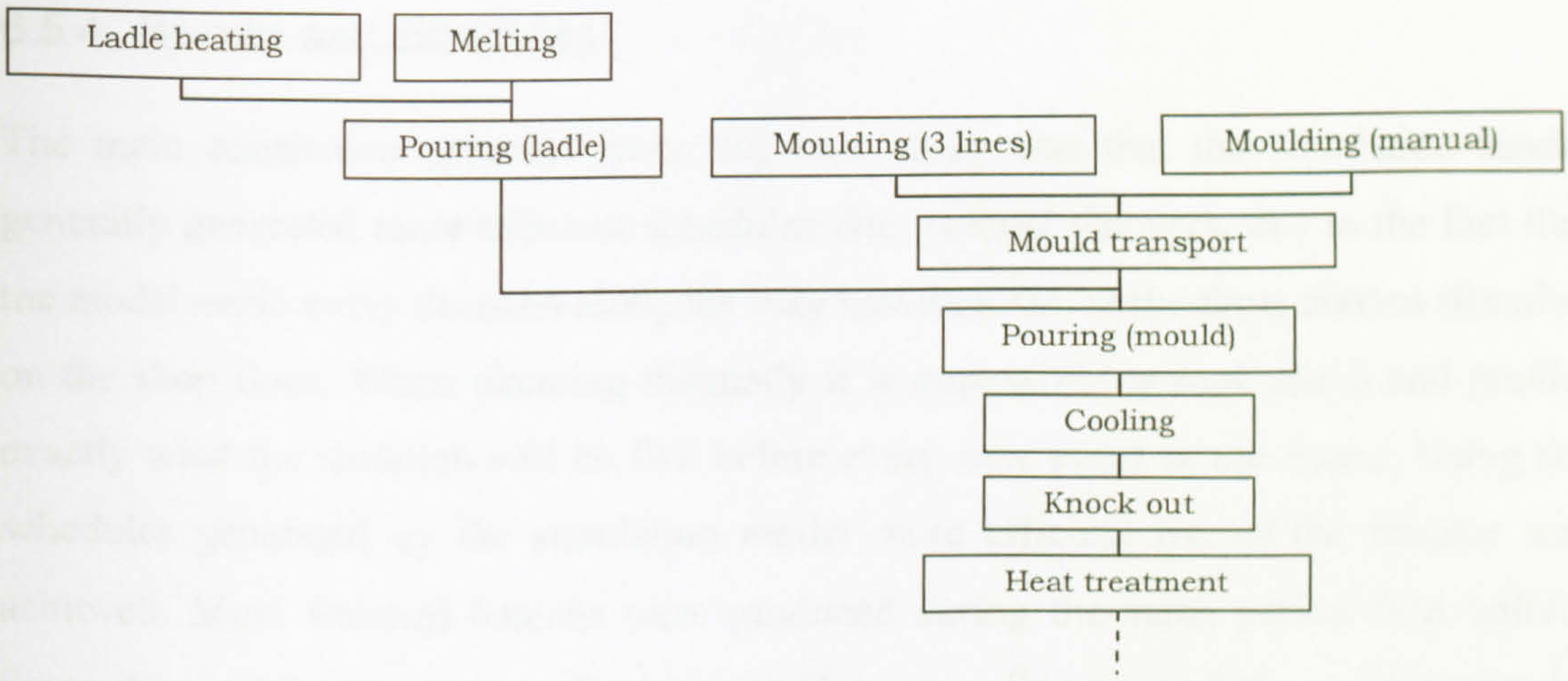


Figure 38.Main foundry processes at Sandvik AB.

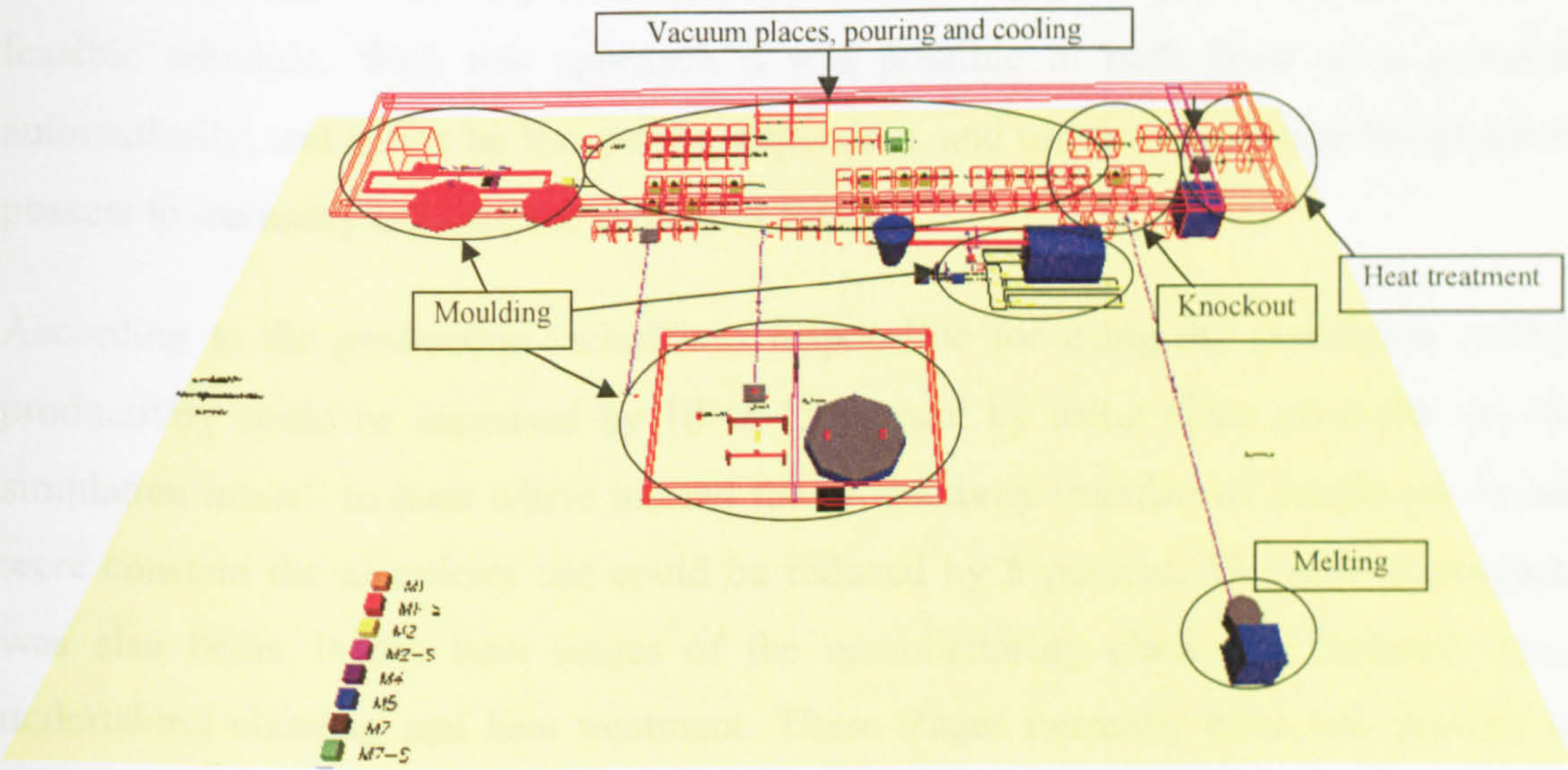


Figure 39.The central parts of the simulation model of Sandvik AB.

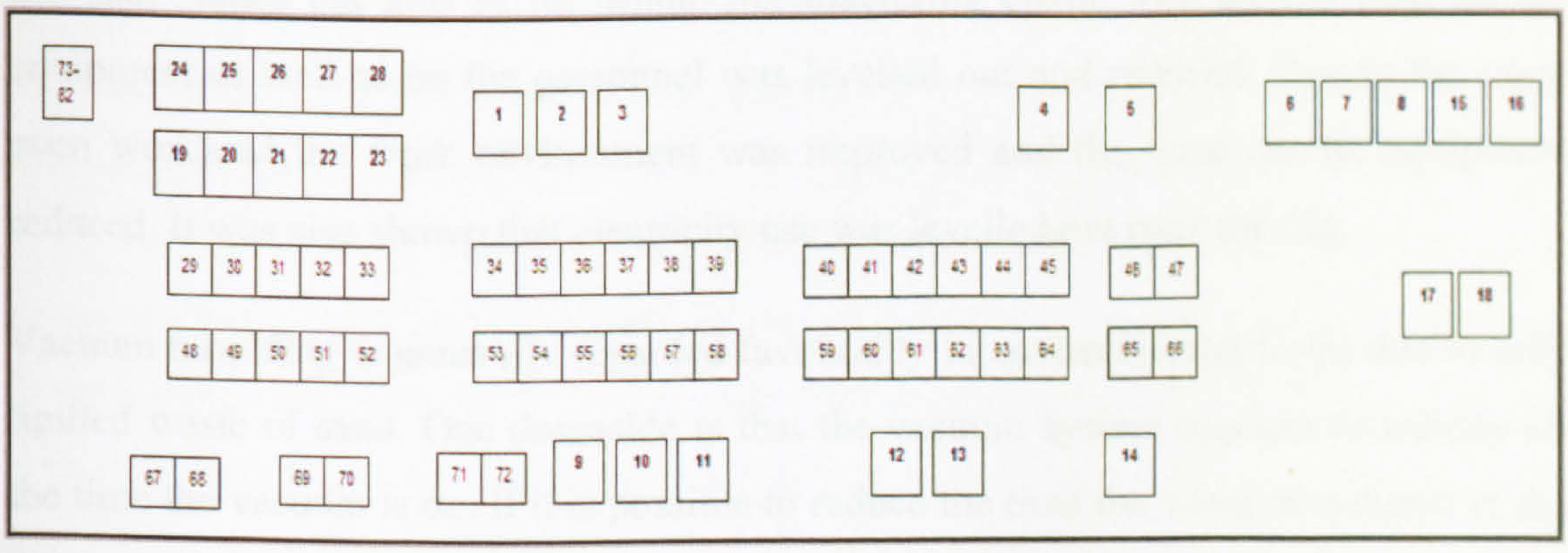


Figure 40.Picture showing possible vacuum stations. The start position is updated with data from the business system before every simulation run. A list of moulds shows which moulds that occupy the numbered vacuum spaces.

6.5.4 Results and discussion

The main conclusion apparent from this case study was that the simulation model generally generated more efficient schedules than manual planners, due to the fact that the model made every decision along the way based on the, at the time, current situation on the shop floor. When planning manually it is impossible to look ahead and predict exactly what the situation will be like before every new event in the future. Using the schedules generated by the simulation model more efficient use of the furnace was achieved. More finished batches were produced during the same period than before. Since the model can calculate the best schedule according to predefined rules and the plan can be altered manually afterwards, there are very good possibilities to obtain a feasible schedule. With this approach it was possible to both draw up a schedule automatically, and hence be less person-dependent, and use the experience the planners possess to manually enhance the schedules further.

According to the production technicians responsible for using the simulation model, productivity could be increased by 10 to 15 percent by using plans generated by the simulation model. In tests where instead the productivity (number of details produced) were constant the electricity use could be reduced by 5 percent. The mix of products was also better in the later stages of the manufacturing chain, for instance when undertaking cleaning and heat treatment. These stages normally have low priority in planning and scheduling. It was also shown that improvements were made not only at the later stages but also in the whole manufacturing chain. The overall load on the equipment as well as on the personnel was levelled out and reduced. Due to the more even workload the work environment was improved and the wear on the equipment reduced. It was also shown that electricity use was levelled out over the day.

Vacuum moulding is generally regarded favourably in environmental terms due to only limited waste of sand. One downside is that the vacuum system requires electricity all the time the vacuum is on. If it is possible to reduce the time the vacuum is active in the mould then electricity use can be reduced. With more efficient schedules lead times can be reduced and hence also the use of the vacuum system.

6.6 Summary of industrial case studies

Four case studies were carried out during this research. The simulation models built in the four case studies are based on the conceptual solution presented in chapter 5. The results from the specific simulation case studies are presented in this chapter and the general analysis and discussions are outlined in chapter 7.

The case studies are used as a means of testing the usability of the methodology. Two different simulation programs were used to show that the methodology is not program-specific. Full verification of that can not be guaranteed due to the fact that several more COTS programs exist on the market. It was decided to use multiple case studies with slightly different objectives to be able to evaluate various aspects of the methodology. The companies at which the case studies were carried out are all sand casting foundries. The companies range from small to medium-sized and produce castings with different materials and sizes.

Most foundry processes have been included in the case study models. In general most benefits can be made from analysing the melting furnaces and the moulding stations or lines. However when analysing the whole system and the power load levels all processes have to be included. Including all processes increases the modelling times significantly so it is important to in an early stage decide what the problem and the objective of the case study are to minimise the time spent in relation to the possible benefits from building the simulation model.

The case studies showed that it is possible to build simulation models that can be used to analyse electricity and power use as well as productivity aspects. The models are described and the most important aspects and results are discussed. One case study has shown the potential to reduce power use throughout the plant and all showed a potential to reduce electricity use. It has been proven that the methodology work for processes in a sand foundry and it will work for other electricity intensive industries with the same and similar processes.

7 Discussion, conclusions and future directions

This chapter will present discussions of and conclusions drawn from the research conducted. Discussions relate to the methodology formulated and its relation to previous research and to the case studies carried out using this approach. Relations to information presented in the literature review will help the reader understand the contribution to knowledge this research brings to the scientific and industrial community. Finally, some suggestions for future research to further enhance the results of this research programme are made.

7.1 Discussion and conclusions

The first conclusion that can be drawn from the research is that the challenge of managing both the manufacturing system and the electricity system in the same model is very complex. Simulation can play a part in the management of the systems, but full control of the situation requires assistance from support systems and support activities at the company. Only then can the advantages of simulation be fully utilised.

Adding electricity parameters to a simulation model and analysing the model from an electricity use point of view will be simplified using the described methodology. The linkages between electricity data, production data and the logic of the system can be difficult to define. One of the reasons is the complexity of measuring data at the desired level of abstraction. The level of abstraction the modeller wants for the model can not be more detailed than the level at which data can be measured. Furthermore, electricity data might only be measurable in groups of processes making it more complicated to model and attach behaviour to the group of processes. The "production behaviour" of a process can therefore be different from its "electricity behaviour". The methodology described deals with all these issues by categorisation of data and approaches for solving the problems.

Adequate input data is needed. A good energy audit has to be made or there needs to be a supervisory system that can provide the latest data. Information gathering is increased by approximately 50 percent compared to when electricity aspects are not considered. The modelling phase is also more time-consuming. Much of the time spent can be decreased with a more structured approach to gathering electricity data. However, the possibilities to gather data will still vary from company to company.

Often in simulation projects a large amount of time is spent on collecting the input data and the information that builds up the conceptual solution, which is later translated into the simulation model. Often there are several sources of information such as documents, interviews and observations. In the described methodology additional sources of information are added since also electricity related information is needed. This further complicates the verification and the validation of the information that is collected and later also the model that is built. However, several sources of evidence improve the construct validity of the case study [Yin 1994] when it reduces the reliability, which means the possibility of repeating the exact case study once more.

According to Worrell et al. [2003] there is great potential of making energy saving investments more cost-effective by also including the productivity benefits. This further proves that a simulation model that considers both productivity and electricity aspects is more useful than models that consider only one or the other. A further benefit from this is that only one model has to be built instead of one productivity based simulation model and one electricity use model. Using DES this can be done in one model alone.

One possible aim for simulation is to reduce the peak power loads on which the monthly or yearly power subscription cost is based. The benefits of reducing the peak power loads are many. First, the subscription level for the following year will be lower. There will be less risk of reaching the peak subscription level and being fined. Second, there is a possibility that the relationship with the power supplier will be better since the supplier knows that there is less risk that the limits will be reached and that more power can thus be sold to other customers.

The most useful way to use DES for energy management and analysis within the foundry industry is at the strategic and tactical levels and as a support for the operational level in the cases where there is a high level of awareness and where the technical specifications are met. At a strategic level, the focus is on the most electricity intensive equipment to analyse problems with long horizons such as LCC analyses of machines. At a tactical level, more effort has to be put into the support processes to be able to analyse how production can be run efficiently over a week or a month. At this level, production can be planned in such a way that the LMS is used less or the limits set by the LMS lowered. The operational planning level is much more complicated since more integration with other systems and production is required. There is also the problem with the limits set by the LMS, which has an impact on the system that a simulation model can not simulate.

Today's LMS are sophisticated enough to handle most situations that can arise but still rely on mathematical calculations and assumptions about the system. With a closer connection between the LMS and the simulation model there are opportunities for even more efficient systems. For example does the LMS reduce the load on equipment if the forecast is that the power load is close to the peak for that particular hour, even though the system may very soon reduce the load itself, for example if a furnace has finished melting. A simulation model can help the system look forward whilst letting the furnace finish, leading to no disruption to the system.

The problems with energy management in foundries are the complexity of the process, the interactions between the systems and the high requirements as regards the molten metal and its effects on the final product. Depending on what metal is used the window in which the molten metal is satisfactory varies, but the issue is always present. There is also the issue of testing the molten metal before pouring which is both time-consuming and can cause extra work if the alloy is not correct. This phase is difficult to reduce by planning but must be considered. If the melting process slows down the alloy must be analysed again or the final structure and properties of the metal might be other than what was expected.

The methodology proposed makes it possible to calculate a more accurate LCC of new and existing equipment. This is due to the possibilities to include production costs as well as electricity costs connected to that particular equipment. It is also possible to vary the tariffs for electricity over the day and also over weeks, months, and years. One of the limitations of this investigation is that trade within the EU ETS and ECS is not included. But if forecasts of these costs are made they can also be included in the model. If there is a risk of a very high cost due to high electricity costs and high price levels within the EU ETS, then it is possible to analyse how profitable it is to run the facility under these circumstances. It is then worth considering if those extra tonnes of castings are profitable to produce or if they can be produced when conditions are more advantageous.

Hiremath et al. [2007] and Jebaraj and Iniyan [2006] describe different model types used for energy modelling. The vast majority of models described are static and deterministic mathematical models in contrast to DES which is considered dynamic and stochastic. The differences between these different groups of models make them suitable for answering different questions. The strengths of DES make it suitable for analysing complex manufacturing systems where situations can change rapidly. Incorporating electricity aspects into a simulation model of a discrete manufacturing system can in a cost effective way combine analysis of the manufacturing processes together with electricity use, power levels and other costs connected to the manufacturing system. In a DES model every event created is based on the system and its parameters at the exact time when the event is created. This makes it possible to analyse the dynamic behaviour of the system making it easy to also analyse, for example, power levels over time. DES used as an analysis tool for modelling and simulation of energy systems certainly helps fill gaps in the energy system modelling map, see Figure 41.

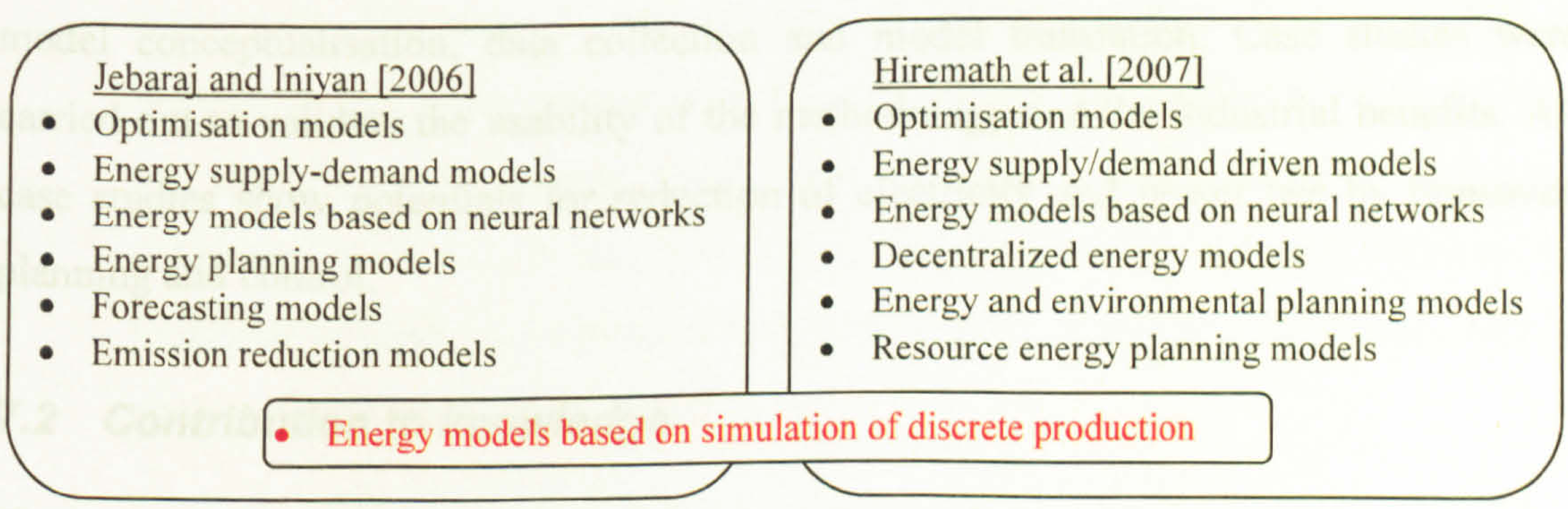


Figure 41.Simulation models of discrete production can serve as a new category of models for energy analysis.

In conducting this research two different DES programs have been used. In the author's experience there are no significant differences between using one or the other. The methodology itself is thus fairly independent of the program used, even though the actual modelling of course differs. However, using less advanced simulation programs may cause problems in formulating advanced simulation models of this type but this has not been analysed within the scope of this research.

The methodology is general and can be applicable to other industries outside the Swedish foundry industry. Most iron foundries in Western countries are like the ones in Sweden and as such could benefit from the approach devised. Differences may exist in the way electricity and power tariffs are structured, which may affect the way the foundry is operated and therefore also the use of electricity intensive equipment.

The methodology is general also in the sense that other industries outside the foundry industry can use it if the processes are similar and use electricity. Additional categories might be identified in other industries. Further case studies in other industry sectors are needed to examine this. In the thesis there is a list of what groups of industries that are considered to be energy intensive according to the Swedish Energy Agency [SEA 2007c].

The main aim of this research study was to create a methodology for improved energy management of industrial plants through the use of DES in the production planning and control process with focus on electricity use. The thesis has presented a methodology and the structured approach the methodology presents means that less time is spent on model conceptualisation, data collection and model translation. Case studies were carried out to validate the usability of the methodology and the industrial benefits. All case studies show potentials for reduction of electricity and power use by improved planning and control.

7.2 Contribution to knowledge

The scientific contribution to knowledge from this study includes:

- The research study demonstrates how theories and methodologies from applied simulation can be utilised in energy management. The research has gone beyond existing studies and applications for DES, which has opened doors for further use of DES within energy and environmental studies.

- The research study has given the analysts of energy systems a new usable tool for conducting energy systems analysis. A DES model complements existing models used within the energy system community.

- The study has identified how to represent electricity input data to make it applicable in DES modelling. Four main categories, which can be used for handling input data of different types, have been defined. The use of these categories is applicable to data from processes with different behaviour.

- The study has identified how to use output data from simulation models to make good representations of the electricity and power use of the system under assessment. Different time steps are used depending on the type of analysis and the time steps are changeable for conducting different types of analysis with the same model. Dividing time into time steps also makes it possible to monitor average power use in smaller intervals with less data to handle.

This research's contribution to industrial knowledge and practice includes:

- Energy audits and analysis made of a company are performed as snapshot analyses. The results are analysed and are often forgotten or obsolete soon afterwards. The same is true of many simulation projects. The methodology devised in this study can increase the use of data collected from energy audits and therefore make energy audits even more useful. For companies that have developed their use of data monitoring and control this can also increase the incentive to work with simulation on a day to day basis since two issues can be analysed at the same time.

- The research study demonstrates how the results from advanced energy audits in industry can be incorporated into a simulation model and analysed for reducing the total electricity use and peak power loads. This can be achieved via improved production planning. It can be applied to either an entire shop floor or to the most electricity intensive production equipment.

- It has been demonstrated that a well formulated simulation model can answer questions about electricity and power use as well as productivity which expands the use of DES models. Hence, the cost of the simulation model in correlation to its use decreases.

7.3 Further comments on simulation

Simulation has proven to be a tool well suited for analysing a company's electricity use and power use levels. However, it should not be believed that simulation is the tool that on its own will decrease a company's energy use. First of all, the need for energy audits is obvious before making a simulation model in order to obtain the accurate input data required. Energy audits can in themselves often help companies be aware of their situation and create a unified view shared by everyone at the company. The importance of viewing the production system as a system working together and interacting with each other, instead of separate departments working under the same roof cannot be stressed enough.

New technology is also an important thing to consider. Planning the facilities in a more efficient way is good but to further trim the system there is a need for new and more energy efficient technology, equipment and processes. The process of investing in new equipment can itself use simulation for verifying that the right equipment is bought, taking into account both productivity and energy issues.

7.4 Future directions

The findings of this research study have proven that DES could be a tool well-suited for analysing energy use in industry. Future research within this area could include the following:

- The data collection and integration used in all four case studies can fit into the second level (of four) of the model from Robertson and Perera [2002]. Data in this research is mainly entered in spreadsheets manually and read to the simulation application automatically. There is a possibility to climb one or two steps in this ranking with increased integration with surrounding systems. But these different systems, ERP and LMS etc., are complicated and the benefits of that approach and the large amount of time it would demand, is difficult to justify unless the company is highly motivated to work with this simulation approach.

- There is potential for improvement of the methodology devised. Adding additional features to the simulation algorithms, such as optimisation techniques is one way. Important issues to take into consideration are that optimisation should not be made strictly from an energy reduction point of view. It is still very important that the productivity of the system is considered as well. One interesting approach for improving the use of DES is to combine DES with other methods and energy models such as optimisation with for example MILP-algorithms.

- This research has focused on electricity. Further work is needed to include processes that use other energy sources. Some experiments have been made including ladle heating with LPG and the basis of the methodology - data management, categorisation and modelling - works in the same way for this process. More developments and experiments are needed to draw general conclusions.

- Since many production facilities have some sort of recycling of excess heat there might be some point to including these aspects in the simulation model as well. This approach will demand a great deal of the modeller in terms of knowledge of energy conservation, energy reuse and the behaviour of energy in air, water and other media. It also demands a closer mapping of things that affect the temperature of energy carriers such as the shapes and sizes of the buildings and outside weather conditions. It also demands information about the losses of heat from ladles, furnaces and cooling moulds due to temperature differences with the surrounding environments.

- The methodology presented has a way of representing electricity and power use in which the resources are the cause of use and also the focus of improvements. However, the products' role in electricity use is not to be underestimated. Larger and heavier products cause an increase in electricity and power use in some resources such as moulding sand preparation. On the other hand, larger and heavier products demand less electricity on average per kilogram in resources such as fettling and grinding. This variation is an interesting issue to be further investigated and simulated. This will further enhance the possibilities to produce an accurate LCA of a product to determine a product's impact on the environment and CO_2 emissions.

- The methodology presented and the categories for representing the power use of processes are formulated from a foundry perspective. Other energy intensive industries will be possible to model with the same approach and categories. However, to investigate the behaviour of special processes in other industries further case studies are needed. These processes might show a behaviour that will increase the number of categories. Other industries outside the foundry industry are, according to the Swedish Energy Agency (SEA) [SEA 2007c] (category names abbreviated): paper, pulp, cement and lime, mines, limestone quarries, basic chemistry, refineries, timber and wood, iron and steel, foundries, metals (others), salt mines and paper articles. Furthermore, applying the methodology to foundries outside Sweden will follow the same procedure as when applied to a Swedish foundry. The processes are more or less the same in most sand casting foundries, at least in Western countries. Differences in the way production is planned will naturally mean differences in the logic of the model. These differences are as large between companies in Sweden as they are between companies in different countries. The largest differences lie in the approach to the electricity and the power use of equipment. Most countries in continental Europe have higher electricity prices than Sweden and also use different subscription schemes. Work environment legislation differs and heating and cooling demands also differ. All these factors will have an impact on how electricity and power is used, what energy carriers are used and also when during the day work is allowed.

References

[Appelqvist and Lehtonen 2002]

Appelqvist, P. and Lehtonen, J-M. (2002) Increasing Productivity in Steel Making: Case Rautaruukki with Delfoi Planner, *Proceedings of the 33rd International Symposium on Robotics*, Stockholm, Sweden.

[Arrhenius 1896]

Arrhenius, S. (1896) On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, *Philosophical Magazine 41*, pp. 237-276.

[Arrhenius 1908]

Arrhenius, S. (1908) *Worlds in the Making*, Harper & Brothers, USA.

[Banks 1998]

Banks, J. (ed) (1998) *Handbook of simulation – Principles, Methodology, Advances, Applications, and Practice*, John Wiley & Sons, Inc.

[Banks 2000]

Banks, J. (2000) Introduction to simulation, *Proceedings of the 2000 Winter Simulation Conference*, Orlando, FL, USA.

[Banks et al. 2003]

Banks, J., Hugan, J. C., Lenderman, P., McLean, C., Page, E. H., Pegden, C. D., Ulgen, O. and Wilson, J. R. (2003) The future of the simulation industry, *Proceedings of the 2003 Winter Simulation Conference*, New Orleans, LA, USA.

[Banks et al. 2005]

Banks, J., Carson, J. S., Nelson, B. L., and Nicol, D. M. (2001) *Discrete-event system simulation*, 4th edition, Prentice-Hall International Series in Industrial and Systems Engineering, Upper Saddle River, USA.

[Barton et al. 2003]

Barton, R. R., Fishwick, P. A., Henriksen, J. O., Sargent, R. G. and Twomey, J. M. (2003) Panel: Simulation – Past, Present and Future, *Proceedings of the 2003 Winter Simulation Conference*, New Orleans, LA, USA.

[Bengtsson et al. 2002]

Bengtsson, C., Karlsson, M., Berntsson, T. and Söderström, M. (2002) Co-ordination of pinch technology and the MIND method – applied to a Swedish board mill, *Applied Thermal Engineering 22*, pp. 133-144.

[Bhatt 2000]

Bhatt, M. S. (2000) Energy audit case studies I – steam systems, *Applied Thermal Engineering 20*, pp. 285-296.

[Boer et al. 2006]

Boer, C. A., de Bruin, A. and Verbraeck, A. (2006) Distributed Simulation in Industry – A Survey, Part 1 – the COTS Vendors, *Proceedings of the 2006 Winter Simulation Conference*, Monterey, CA, USA.

[Boyd and Pang 2000]

Boyd, G. A. and Pang, J. X. (2000) Estimating the linkage between energy efficiency and productivity, *Energy Policy 28*, pp. 289-296.

[Brady 2001]

Brady, T. (2001) Computer simulation analysis of electricity rationing effects on steel mill rolling operations, *Proceedings of the 2001 Winter Simulation Conference*, Arlington, VA, USA.

[Brady 2002]

Brady, T. F. (2002) Using computer simulation to mitigate risk in electricity generation/consumption collaboration policies, *Proceedings of the 2002 Winter Simulation Conference*, San Diego, CA, USA.

[BrooksSoftware 2007]

BrooksSoftware (2007) <www.brookssoftware.com> [accessed January 5, 2006].

[Bryman 2001]

Bryman, A. (2001) *Social Research Methods*, Oxford University Press, Oxford, England.

[CAEF 2006]

CAEF (The European Foundry Association) (2006) *The European Foundry Industry 2005*, CAEF, Düsseldorf, Germany.

[Centeno and Carrillo 2001]

Centeno, M. A. and Carrillo, M. (2001) Challenges of introducing simulation as a decision making tool, *Proceedings of the 2001 Winter Simulation Conference*, Arlington, VA, USA.

[Checkland 1999]

Checkland, P. (1999) *Systems Thinking, Systems Practice – Includes a 30-year retrospective*, John Wiley & Sons, Ltd., Chichester, England.

[Chong et al. 2003]

Chong, C. S., Sivakumar, A. I. and Gay, R. (2003) Simulation-Based Scheduling for Dynamic Discrete Manufacturing, *Proceedings of the 2003 Winter Simulation Conference*, New Orleans, LA, USA.

[Churchman 1968]

Churchman, C. W. (1968) *The system approach*, Dell Publishing, New York, USA.

[COM 2006]

COM (European Commission) (2006) *Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC*, Brussels.

[Dalal et al. 2003]

Dalal, M., Groel, B. and Prieditis, A. (2003) Real-Time Decision Making Using Simulation, *Proceedings of the 2003 Winter Simulation Conference*, New Orleans, LA, USA.

[Dane 1990]

Dane, F. C. (1990) *Research Methods*, Brooks/Cole Publishing Company, Pacific Grove, USA.

[Das et al. 2000]

Das, B. P., Rickard, J. G., Shah, N. and Macchietto, S. (2000) An investigation on integration of aggregate production planning, master production scheduling and short-term production scheduling of batch process operations through a common data model, *Computers and Chemical Engineering 24*, pp. 1625-1631.

[Davis 1999]

Davis, W. J. (1999) Simulation: Technologies in the New Millennium, *Proceedings of the 1999 Winter Simulation Conference*, Phoenix, AZ, USA.

[DETR 1999]

DETR (Department of the Environment, Transport and the Regions) (1999) *Good practice guide 17.* Achieving high yields in iron foundries. DETR. Harwell. UK.

[Dewhurst et al. 2001]

Dewhurst, F., Barber, K. and Rogers, J. J. B. (2001) Towards integrated manufacturing planning with common tool and information sets, *International Journal of Operations & Production Management*, Vol. 21, No. 11, pp. 1460-1482.

[Directive 96/92/EC]

Second report to the council and the European Parliament on harmonisation requirements – Directive 96/92/EC concerning common rules for the internal market in electricity.

[Eriksson 2005]

Eriksson, U. (2005) *Diffusion of Discrete Event Simulation in Swedish Industry – On the Way to an Increased Understanding*, PhD Thesis, Department of Materials and Manufacturing Technology, Chalmers University of Technology, Göteborg, Sweden.

[EU ETS 2007]

EU ETS (2007) <http://ec.europa.eu/environment/climat/emission.htm>, [accessed September 4 2007].

[Eurostat 2006]

Eurostat (2006) *Statistics in focus – environment and energy 4/2006.* Authors: Goerten and Clement, European Communities, ISSN 1562-3106.

[ExpertFit 2007]

ExpertFit (2007) <www.averill-law.com/Expert-Fit-ditribution-fitting-software.htm>, [accessed February 19 2007].

[Fishwick 1995]

Fishwick, P. A. (1995) *Simulation Model Design and Execution: Building Digital Worlds*, Prentice Hall International Series in Industrial and Systems Engineering, New Jersey, USA.

[Freeman et al. 1997]

Freeman, S. L., Niefer, M. J. and Roop, J. P. (1997) Measuring industrial energy intensity: practical issues and problems, *Energy Policy*, Vol 25, pp 703-714.

[Fritzson and Berntsson 2006]

Fritzson, A. and Berntsson, T. (2006) Efficient energy use in a slaughter and meat processing plant – opportunities for process integration. *Journal of Food Engineering 76*, pp. 594-604.

[Geller et al. 2006]

Geller, H., Harrington, P., Rosenfeld, A. H., Tanishima, S. and Unander, F. (2006) Polices for increasing energy efficiency: Thirty years of experience in OECD countries, *Energy Policy 34*, pp 556-573.

[Gong and Karlsson 2004]

Gong, M. and Karlsson, M. (2004) Coordination of exergy analysis and the MIND method – applied to a pulp and board mill, *International Journal of Exergy*, Vol. 1, Nr 3, pp. 289-302.

[Gong and Wall 2001]

Gong, M. and Wall, G. (2001) On exergy and sustainable development – Part 2: Indicators and methods, *Exergy, an International Journal*, Vol. 1, Nr 4, pp. 217-233.

[Gustafsson 1998]

Gustafsson, S-I. (1998) Carpentry factory and municipal electricity loads, *Energy Conversion and Management*, Vol. 39, No. ¾, pp. 343-347.

[Harrington and Tumay 2000]

Harrington, H. J. and Tumay, K. (2000) *Simulation Modeling Methods*, McGraw-Hill, New York, USA.

[Hiremath et al. 2007]

Hiremath, R. B., Shikha, S. and Ravindranath, N. H. (2007) Decentralized energy planning: modeling and application – a review, *Renewable and Sustainable Energy Reviews 11*, pp. 729-752.

[Hlupic 2000]

Hlupic, V. (2000) Simulation Software: An Operational Research Society Survey of Academic and Industrial Users, *Proceedings of the 2000 Winter Simulation Conference*, Orlando, FL, USA.

[Holst et al. 2000]

Holst, L., Randell, L. and Bolmsjö, G. (2000) The integrated use of simulation in the development of manufacturing systems: A study of Japanese industry, *Proceedings of the INFORMS/KORMS Conference on Information and Knowledge Management in the 21st Century*, Seoul, Korea.

[IMTI 2000]

IMTI (2000) Integrated Manufacturing Technology Initiative, [online] Available via <www.IMTI21.org> [accessed April 23, 2007].

[IMTR 2000]

IMTR (2000) *Integrated Manufacturing Technology Roadmapping Project: Modeling & Simulation for Manufacturing*, IMTI, Inc., Oak Ridge, TN, USA. [online] Available via <www.IMTI21.org> [accessed April 23, 2007].

[Incontrol 2007]

Incontrol Enterprise Dynamics, (2007), <www.incontrol.nl>, [accessed February 19 2007].

[Ingelstam 2002]

Ingelstam, L. (2002) *System – att tänka över samhälle och teknik*, Energimyndighetens förlag, Kristianstad, Sweden. (In Swedish)

[Jackson 1998]

Jackson, M. (1998) *Discrete Event Simulation - A Tool to Increase Agility in Production Systems – A Theoretical Study*, Linköping Studies in Science and Technology, Thesis no 721, University of Linköping, Sweden.

[Jain 1999]

Jain, S. (1999) Simulation in the next millennium, *Proceedings of the 1999 Winter Simulation Conference*, Phoenix, AZ, USA.

[Jean-Baptiste and Ducroux 2003]

Jean-Baptiste, P., and Ducroux, R. (2003) Energy policy and climate change, *Energy Policy 31*, pp 155-166.

[Jebaraj and Iniyan 2006]

Jebaraj, S. and Iniyan, S. (2006) A review of energy models, *Renewable and Sustainable Energy Reviews 10*, pp 281-311.

[Johansson et al. 2002]

Johansson, B., Johnsson, J., Eriksson, U. (2002) An evaluation of Discrete Event Simulation software for "Dynamic Rough-Cut Analysis", *The 35th CIRP-International Seminar on Manufacturing Systems*, Seoul, Korea.

[Johtela et al. 1997]

Johtela, T., Smed, J., Johnsson, M., Lehtinen, R. and Nevalainen, O. (1997) Supporting Production Planning by Production Process Simulation, *Computer Integrated Manufacturing Systems*, Volume 10, Number 3.

[Jägstam 2003]

Jägstam, M. (2003) *Method handbook – Industrial production simulation.* Version 1.0. Edited by M. Jägstam and J. Oscarsson. Department of Engineering Science. University of Skövde. Sweden.

[Jägstam 2004]

Jägstam, M. (2004) *On efficient use and integration of discrete event simulation in industry,* Ph.D. Thesis, Faculty of Computer Sciences and Engineering, De Montfort University, Leicester, UK.

[Kannan and Boie 2003]

Kannan, R. and Boie, W. (2003) Energy management practices in SME - case study of a bakery in Germany, *Energy Conversion and Management*, Vol 44, Issue 6, pp. 945-959.

[Kamal 1997]

Kamal, W. A. (1997) Improving energy efficiency – the cost-effective way to mitigate global warming. *Energy Conversion and Management,* Vol 38, No 1, pp. 39-59.

[Karlsson and Söderström 2002]

Karlsson, M. and Söderström, M. (2002) Sensitivity analysis of investments in the pulp and paper industry – on investments in the chemical recovery cycle at a board mill, *International Journal of Energy Research*, Vol. 26, Nr 14, pp. 1253-1267.

[Karlsson 2004]

Karlsson, P. (2004) *Energisystemanalys AB Bruzaholms bruk [Energy system analysis AB Bruzaholms bruk]* (In Swedish).

[Kelton 1997]

Kelton, W. D. (1997) Statistical analysis of simulation output, *Proceedings of the 1997 Winter Simulation Conference*, Atlanta, GA, USA.

[Kelton 2000]

Kelton, W. D. (2000) Experimental Design for Simulation, *Proceedings of the 2000 Winter Simulation Conference*, Orlando, FL, USA.

[Kelton et al. 2004]

Kelton, W. D., Sadowski, R. P. and Sturrock, D. T. (2004) *Simulation with ARENA*, Third Edition, McGraw-Hill Series in Industrial Engineering and Management Science, New York, USA.

[Kidder and Judd 1986]

Kidder, L. and Judd, C. M. (1986) *Research methods in social relations*, Fifth edition, Holt, Rinehart & Winston, New York, USA.

[Klingstam and Gullander 1999]

Klingstam, P. and Gullander, P. (1999) Overview of simulation tools for computer-aided production engineering, *Computers in Industry 38*, pp. 173-186.

[Klingstam 2001]

Klingstam, P. (2001) *Integrating Discrete Event Simulation into the Engineering Process – Strategic Solutions for Increased Efficiency in Industrial System Development*, Ph.D. Thesis, Department of Production Engineering, Chalmers University of Technology.

[Kleijnen and van Groenendaal 1992]

Kleijnen, J. P. C. and van Groenendaal, W. (1992) *Simulation: A Statistical Perspective*, John Wiley & Sons, Chichester, England.

[Koh et al. 1996]

Koh, K-H., de Souza, R. and Ho, N-C. (1996) Database driven simulation/simulation-based scheduling of a job-shop, *Simulation Practice and Theory 4*, 31-45.

[Kuiper 1998]

Kuiper, D. (1998) The Key to a Custom Fit, *OR/MS Today*, Vol. 1, Nr 1, Lionheart Publishing, Inc., Atlanta, USA, [online] Available via <http://www.lionhrtpub.com/orms> [accessed April 27 2007].

[Kvale 1996]

Kvale, S. (1996) *Interviews: An Introduction to Qualitative Research Interviewing.* SAGE publications, Thousand Oaks, USA.

[Landeghem and Vanmaele 2002]

Landeghem, H. V. and Vanmaele, H. (2002) Robust planning: a new paradigm for demand chain planning, *Journal of Operations Management 20*, pp. 769-783.

[Larsen and Jensen 1999]

Larsen, A. and Jensen, M. (1999) Evaluations of energy audits and the regulator, *Energy Policy 27*, pp 557- 564.

[Law 2003]

Law, A. M. (2003) How to conduct a successful simulation study, *Proceedings of the 2003 Winter Simulation Conference*, New Orleans, LA, USA.

[Law 2007]

Law, A. M. (2007) *Simulation Modeling and Analysis.* McGraw-Hill Series in Industrial Engineering and Management Science, McGraw-Hill, Inc., Fourth Edition, New York, USA.

[Lehtonen et al. 2003]

Lehtonen, J-M., Appelqvist, P., Ruohola, T. and Mattila, I. (2003) Simulation-Based Finite Scheduling at Albany International, *Proceedings of the 2003 Winter Simulation Conference*, New Orleans, LA, USA.

[LiU 2003a]

LiU (Linköping University) (2003) *Energisystemanalys av SKF Mekan AB: Del 1: Analys*, Linköping University in cooperation with Swedish Foundry Association. (In Swedish)

[LiU 2003b]

LiU (Linköping University) (2003) *Energisystemanalys av SKF Mekan AB: Del 2: Förbättringsförslag*, Linköping University in cooperation with Swedish Foundry Association. (In Swedish)

[Mazziotti and Horne 1997]

Mazziotti, B. W. and Horne Jr, R. E. (1997) Creating a Flexible, Simulation-Based Finite Scheduling Tool, *Proceedings of the 1997 Winter Simulation Conference*, Atlanta, GA, USA.

[McLean and Leong 2001]

McLean, C., and Leong, S. (2001) The expanding role of simulation in future manufacturing, *Proceedings of the 2001 Winter Simulation Conference*, Arlington, VA, USA.

[McNally and Heavey 2002]

McNally, P. and Heavey, C. (2002) Simulation as a Desktop Resource: The Limitations and Future Requirements of Simulation Technologies. *Proceedings of the 19th International Manufacturing Conference*, Belfast, Northern Ireland.

[Merriam 1998]

Merriam, S. B. (1998) *Qualitative Research and Case Study Applications in Education*, Jossey-Bass, Inc. Publishers, San Fransisco, USA.

[Miketa and Mulder 2005]

Miketa, A. and Mulder, P. (2005) Energy productivity across developed and developing countries in 10 manufacturing sectors: Patterns of growth and convergence, *Energy Economics 27*, pp 429-453.

[Mori et al. 2004]

Mori, K., Kitamura, S., Shindo, S. (2004) Simulation-Based Scheduling System For Saving Energy Consumption, *Proceedings of the SICE Annual Conference in Sapporo*, Sapporo, Japan.

[Musselman 1994]

Musselman, K. (1994) Guidelines for simulation project success, *Proceedings of the 1994 Winter Simulation Conference*, Orlando, FL, USA.

[Musselman et al. 2002]

Musselman, K., O'Reilly, J. and Duket, S. (2002) The Role of Simulation in Advanced Planning and Scheduling, *Proceedings of the 2002 Winter Simulation Conference*, San Diego, CA, USA.

[Nordgren 1995]

Nordgren, W. B., (1995) Steps for proper simulation project management, *Proceedings of the 1995 Winter Simulation Conference*, Arlington, VA, USA.

[OECD 2004]

OECD (Organization for Economic Cooperation and Development) (2004) *OECD key environmental indicators*. Paris. France. [online] Available via <http://www.oecd.org/dataoecd/32/20/31558547.pdf> [accessed April 1, 2006].

[OR/MS Survey 2005]

OR/MS Survey (2005) Simulation software survey, *OR/MS Today*, December 2005, Lionheart Publishing, Inc., Marietta, USA, [online] Available via <http://www.lionhrtpub.com/orms/surveys/Simulation/Simulation.html> [accessed April 27 2007].

[Pal and Huff 2000]

Pal, J. K. and Huff, F. C. (2000) - Advantages of an electrical control and energy management system, *ISA Transactions 39*, pp.103-114.

[Page 1994]

Page, E. H. Jr. (1994) *Simulation modeling methodology: principles and etiology of decision support*, PhD Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.

[Pegden et al. 1995]

Pegden, C. D., Shannon, R. E., and Sadowski, R. P. (1995) *Introduction to Simulation Using SIMAN*, Second Edition, McGraw-Hill, Inc., New York, USA.

[Perera and Liyanage 2000]

Perera, T., and Liyanage, K. (2000) Methodology for rapid identification and collection of input data in the simulation of manufacturing systems, *Simulation Practice and Theory 7*, pp.645-656.

[Perera and Liyanage 2001]

Perera, T., and Liyanage, K. (2001) IDEF based methodology for rapid data collection, *Integrated manufacturing systems*, Volume 12, Issue 3, pp.187-194.

[Pidd 2004]

Pidd, M. (2004) *Computer Simulation in Management Science*, Fifth edition, John Wiley & Sons, Ltd., Chichester, England.

[Porter and van der Linde 1995]

Porter M. E., van der Linde, C. (1995) Green and Competitive: Ending the Stalemate, *Harvard Business Review*, Vol. 73 Issue 5, pp. 120-133.

[Randell and Bolmsjö 2001]

Randell, L. G. and Bolmsjö, G. S. (2001) Database Driven Factory Simulation: A Proof-of-Concept Demonstrator, *Proceedings of the 2001 Winter Simulation Conference*, Arlington, VA, USA.

[Rizzi and Zamboni 1999]

Rizzi, A. and Zambini. R. (1999) Efficiency improvement in manual warehouses through ERP systems implementation and redesign of the logistics processes, *Logistics Information Management*, Volume 12, Number 5, pp 367-377.

[Robertson and Perera 2002]

Robertson, N., and Perera, T. (2002) Automated data collection for simulation?, *Simulation Practice and Theory 9*, pp. 349-364.

[Robinson 1994]

Robinson, S. (1994) *Successful Simulation: A Practical Approach to Simulation Projects*, McGraw-Hill Book Company Europe, Berkshire, England.

[Robinson 2006]

Robinson, S. (2006) Conceptual modeling for simulation: issues and research requirements. *Proceedings of the 2006 Winter Simulation Conference*, Monterey, CA, USA.

[Rohdin and Thollander 2006a]

Rohdin, P. and Thollander, P. (2006) Barriers to and Driving Forces for Energy Efficiency in the Non-energy Intensive Manufacturing Industry in Sweden. *Energy*, Volume 31, Issue 12.

[Rohdin and Thollander 2006b]

Rohdin, P. and Thollander, P. (2006) *Hinder och drivkrafter för energieffektivisering i svensk gjuteriindustri*, Linköpings Universitet, Sweden. (In Swedish)

[Rohdin and Moshfegh 2007]

Rohdin, P. and Moshfegh, B. (2007) Numerical predictions of indoor climate in large industrial premises. A comparison between different k–ε models supported by field measurements, *Building and Environment 42*, pp. 3872-3882.

[Rohdin et al. 2007]

Rohdin, P., Thollander, P. and Solding, P. (2007) Barriers to and drivers for energy efficiency in the Swedish foundry industry, *Energy Policy,* Volume 35, Issue 1.

[Sadowski 1993]

Sadowski, R. (1993) Selling simulation and simulation results, *Proceedings of the 1993 Winter Simulation Conference*, Los Angeles, CA, USA.

[Sadowski and Grabau 2000]

Sadowski, D. A. and Grabau, M. R. (2000) Tips for successful practice of simulation, *Proceedings of the 2000 Winter Simulation Conference*, Orlando, FL, USA.

[Sandberg and Söderström 2003]

Sandberg, P. and Söderström, M. (2003) Industrial energy efficiency: the need for investment decision support from a manager perspective, *Energy Policy 31*, pp 1623-1634.

[Sargent 2004]

Sargent, R. G. (2004) Validation and verification of simulation models, *Proceedings of the 2004 Winter Simulation Conference,* Washington, DC, USA.

[SCB 2007]

SCB (Statistiska Centralbyrån) (2007) Statistics from SCB, [online] Available via <http://www.scb.se>, [accessed April 25 2007].

[SEA 2006a]

SEA (Swedish Energy Agency) (2006) *Energy in Sweden 2006*, report nr: ET2006:45w, Energimyndighetens förlag, [online] Available via <www.energimyndigheten.se/web/ biblshop.nsf>, [accessed April 12 2007].

[SEA 2006b]

SEA (Swedish Energy Agency) (2006) *Renewable electricity through electricity certificates*, report nr: ET2006:54, Energimyndighetens förlag, [online] Available via <www.energimyndigheten.se/web/ biblshop.nsf>, [accessed September 4 2007].

[SEA 2007a]

SEA (Swedish Energy Agency) (2007) <www.energimyndigheten.se>

[SEA 2007b]

SEA (Swedish Energy Agency) (2007) *Energimarknadsinspektionen 2006 [Energy Markets Inspectorate 2006]* (in Swedish), report nr: ET:2007:06 Energimyndighetens förlag, [online] Available via <www.energimyndigheten.se/web/biblshop.nsf> [accessed April 14 2007].

[SEA 2007c]

SEA (Swedish Energy Agency) (2007) *Europeiska utsläppshandelssystemets påverkan på industrin – en underlagsrapport*, (in Swedish), report nr: ET:2007:08 Energimyndighetens förlag, [online] Available via <www.energimyndigheten.se/web/biblshop.nsf> [accessed April 14 2007].

[SEA 2007d]

SEA (Swedish Energy Agency) (2007) *Två år med PFE – De första redovisade resultaten,* (in Swedish), report nr: ET:2007:10 Energimyndighetens förlag, [online] Available via <www.energimyndigheten.se/web/biblshop.nsf>*ceedings of the 1997 Winter Simulation Conference*, Atlanta, GA, USA.

[Spata 2003]

Spata, A. V. (2003) *Research Methods: Science and Diversity*, International Edition, John Wiley & Sons, Inc., New York, USA.

[Stake 1995]

Stake R. E. (1995) *The Art of Case Study Research*, Sage Publications, Inc., Thousand Oaks, USA.

[Stat::Fit 2007]

Stat::Fit, www.geerms.com, accessed February 19, 2007.

[Sule 1997]

Sule, D. R. (1997) *Industrial Scheduling*, PWS Publishing Company, Boston, USA.

[Svensson 2001]

Svensson, I. L. (2001) *Component Casting with Simulation*, School of Engineering, Jönköping University, Sweden.

[Swain 1997]

Swain, J. J. (1997) Simulation Goes Mainstream, *OR/MS Today*, Vol. 24, No. 5, Lionheart Publishing, Inc., Marietta, USA, [online] Available via <http://www. lionhrtpub.com/orms/ORMS-archive.html> [accessed April 27 2007].

[Swain 1999]

Swain, J. J. (1999) Imagine new worlds, *OR/MS Today*, February 1999, Lionheart Publishing, Inc., Marietta, USA, [online] Available via < http://www.lionhrtpub.com/orms/ORMS-archive.html> [accessed April 27 2007].

[Swerea SWECAST 2007a]

Swerea SWECAST (2007). *2006 - ett nytt rekordår för de svenska gjuterierna - Gjuteribranschen fortsatt het.* [2006 – A new record year for the Swedish foundries – The foundry industry is still hot], (in Swedish), [online] Available via <http://www.gjuteriforeningen.se/aktuellt/pressrelease0703.pdf> [accessed June 19 2007].

[Swerea SWECAST 2007b]

Swerea SWECAST (2007) *Database of Swedish foundries – members of the Swedish Foundry Association,* Database is organised by Swerea SWECAST by request from the Swedish Foundry Association.

[Thollander et al. 2005]

Thollander, P., Karlsson, M., Söderström, M. and Creutz, D. (2005) Reducing industrial energy costs through energy efficiency measures in a liberalized European electricity market - case study of a Swedish iron foundry, *Applied Energy* 81 (2), 115-126.

[Thollander 2008]

Thollander, P. (2008) *Drivkrafter för energieffektivisering i svensk gjuteriindustri,* Linköpings Universitet, Sweden. (In Swedish)

[Trybula 1994]

Trybula, W. (1994) Building simulation models without data, *1994 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 209-214.

[Trygg and Karlsson 2005]

Trygg, L. and Karlsson, B. (2005) Industrial DSM in a deregulated European electricity market - a case study of 11 plants in Sweden, *Energy Policy,* Volume 33 Issue 11, 1445-1459.

[Trygg 2006]

Trygg, L. (2006) *Swedish Industrial and Energy Supply Measures in a European System Perspective*, PhD Thesis, Division of Energy Systems, Linköping University, Sweden.

[Umeda and Jones 1997]

Umeda S., and Jones, A. (1997) *Simulation in Japan: State-of-the-art update*, Technical report NISTIR 6040, National Institute of Standards and Technology, U.S. Department of Commerce.

[US GAO 1990]

US GAO (United States General Accounting Office) (1990) *Case Study Evaluation*, Program Evaluation and Methodology Division, Washington, DC, USA. [online] Available via <http://www.gao.gov/special.pubs/10_1_9.pdf> [accessed April 27, 2007].

[Wall and Gong 2001]

Wall, G. and Gong, M. (2001) On exergy and sustainable development – Part 1: Conditions and concept, *Exergy, an International Journal*, Vol. 1, Nr 3, pp. 128-145.

[Watkins 1993]

Watkins, K. (1993) *Discrete Event Simulation in C*, McGraw-Hill Book Company Europe, Berkshire, England.

[Williams 1996]

Williams, E. (1996) Making Simulation a Corporate Norm, *Proceedings of the 1996 Summer Computer Simulation Conference*, USA.

[Worrell et al. 2003]

Worrell, E., Laitner, J. A., Ruth, M. and Finman, H. (2003) Productivity benefits of industrial energy efficiency measures. *Energy* 28, 1081-1098.

[WSC]

WSC (Winter Simulation Conference), *Proceedings of the Winter Simulation Conference*, [online] Available via <www.wintersim.org> [accessed April 27 2007]

[Yin 1993]

Yin, R. K. (1993) *Applications of Case Study Research: Design and Methods*, Sage Publications, Inc., Newbury Park, USA.

[Yin 1994]

Yin, R. K. (1994) *Case Study Research: Design and Methods*, Second edition, Sage Publications, Inc., Thousands Oaks, USA.

[Zhu 2006]

Zhu, Y. (2006) Applying computer-based simulation to energy auditing: A case study, *Energy and Buildings 38*, pp. 421-428.

List of publications

Solding, P., Randell, L. and de Vin, L. (2002) The Simulation Expert's Role as a Catalyst in Discrete Event Simulation Projects, *Proceedings of the 19th International Manufacturing Conference*, Belfast, Northern Ireland.

Solding, P., Eriksson, P. and de Vin, L. (2003) Discrete Event Simulation in Operational Production Planning - An Outline, *Proceedings of the 20th International Manufacturing Conference*, Cork, Ireland.

Solding, P., Andersson, K. M. and de Vin, L. J. (2004) Simulation-Based Scheduling In Automotive Industry, *Proceedings of Modelling and Simulation 2004*, Marina del Ray, Los Angeles, USA.

Solding, p., Nilsson, M., Eriksson, P. and de Vin, L. J. (2004) Structure for Data Management in Simulation Based Planning Activities, *Proceedings of the 37th CIRP International Seminar on Manufacturing Systems*. Budapest, Hungary.

Nilsson, M., Solding, P. and de Vin, L. J. (2004) A System Architecture for Integrated Simulation-Based Planning and Scheduling, *Proceedings of Mechatronics 2004*, Ankara, Turkey.

Solding, P. and Petku, D. (2005) Applying Energy Aspects on Simulation of Energy-Intensive Production Systems, *Proceedings of the 2005 Winter Simulation Conference*, Orlando, USA.

Solding, P. and Thollander, P. (2006) Increased energy efficiency in a Swedish iron foundry through use of discrete event simulation, *Proceedings of the 2006 Winter Simulation Conference*, Monterey, USA.

Thollander, P. and Solding, P. (2006) Barriers to and driving forces for the implementation of manufacturing simulation in the Swedish foundry industry, *2006 Winter Simulation Conference*, Monterey, USA. (Poster)

Rohdin, P., Thollander, P. and Solding, P. (2007) Barriers to and drivers for energy efficiency in the Swedish foundry industry, *Energy Policy*, Volume 35, Issue 1.

Solding, P. (2008) More energy efficient casting without loss of output, *68th World Foundry Congress 2008*, Chennai, India.

Solding, P., Thollander, P. and Moore, P., Improved Energy Efficient Manufacturing Using Discrete Event Simulation, Submitted for Journal Publication

Appendix A - Additional data from case study 1

A.1 Experiment data – Work hours

	A	B	C	D	E	F	G	H	I
1									
2		**Work Hours**							
3									
4		General							
5			**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
6		**Start shift**	06:00	06:00	06:00	06:00	06:00	00:00	00:00
7		**End shift**	09:00	09:00	09:00	09:00	09:00	00:00	00:00
8		**Start shift**	09:30	09:30	09:30	09:30	09:30	00:00	00:00
9		**End shift**	12:00	12:00	12:00	12:00	12:00	00:00	00:00
10		**Start shift**	12:30	12:30	12:30	12:30	12:30	00:00	00:00
11		**End shift**	17:00	17:00	17:00	17:00	17:00	00:00	00:00
12		**Start shift**	17:30	17:30	17:30	17:30	17:30	00:00	00:00
13		**End shift**	19:00	19:00	19:00	19:00	19:00	00:00	00:00
14		**Start shift**	19:30	19:30	19:30	19:30	19:30	00:00	00:00
15		**End shift**	22:30	22:30	22:30	22:30	22:30	00:00	00:00
16									
17									
18		Furnaces							
19			**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
20		**Start shift**	04:00	04:00	04:00	04:00	04:00	00:00	00:00
21		**End shift**	20:30	20:30	20:30	20:30	20:30	00:00	00:00
22									

A.2 Experiment data – Order list

Article number is made anonymous.

	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Artnr	Benämning	Datum	Starttid	Stopptid	Skift	Brätt_Typ	Formade	Kassation	Kassationprocent	Godkända	AntalDetaljer	Detaljvikt
2	A1	Propellernav	2006-01-02	05:39:12	06:11:31	2.00	2	95	2	2.105263	93	186	45
3	A2	Propellernav	2006-01-02	06:12:09	07:52:31	2.00	2	33	4	12.12121	29	58	45
4	A3	Tätningshuslock	2006-01-02	07:52:40	09:27:55	2.00	2	65	0	0	65	65	32
5	A4	Tätningshuslock	2006-01-02	09:28:05	09:48:44	2.00	2	21	1	4.761905	20	40	22
6	A5	Statorhus	2006-01-02	09:48:53	11:31:33	2.00	2	41	0	0	41	328	10
7	A6	Tätningshuslock	2006-01-02	11:31:42	12:20:09	2.00	2	37	0	0	37	74	22
8	A7	Statorhus	2006-01-02	12:20:20	13:19:17	2.00	2	37	1	2.702703	36	288	10
9	A8	Statorhus	2006-01-02	13:27:01	13:43:20	1.00	2	2	0	0	2	16	10
10	A9	Styrklor	2006-01-02	13:43:30	14:12:29	1.00	2	29	0	0	29	232	8
11	A10	Statorhus	2006-01-02	14:13:08	14:45:54	1.00	2	24	2	8.333333	22	44	94
12	A11	Statorhus	2006-01-02	14:45:54	15:18:22	1.00	2	12	0	0	12	24	94
13	A12	Styrklor	2006-01-02	15:18:31	16:03:42	1.00	2	25	0	0	25	200	8
14	A13	Statorhus	2006-01-02	16:03:52	16:30:36	1.00	2	25	1	4	24	72	27
15	A14	Tätningshuslock	2006-01-02	16:30:47	16:50:34	1.00	2	24	0	0	24	24	32
16	A15	Pumphjul	2006-01-02	16:50:44	16:55:45	1.00	2	6	1	16.66667	5	40	4
17	A16	Tätningshuslock	2006-01-02	16:55:54	17:15:30	1.00	2	5	0	0	5	5	32
18	A17	Pumphus	2006-01-02	17:15:40	17:23:43	1.00	2	8	0	0	8	8	116
19	A18	Tätningshuslock	2006-01-02	17:23:53	17:41:29	1.00	2	23	0	0	23	23	32
20	A19	Inloppstratt	2006-01-02	17:41:38	17:46:09	1.00	2	6	0	0	6	6	67
21	A20	Tätningshuslock	2006-01-02	17:46:20	17:59:08	1.00	2	17	0	0	17	17	32
22	A21	Pumphus	2006-01-02	17:59:20	18:12:07	1.00	2	19	0	0	19	19	46
23	A22	Pumphjul	2006-01-02	18:12:18	18:28:49	1.00	2	16	3	18.75	13	26	23
24	A23	Pumphus	2006-01-02	18:28:59	18:51:55	1.00	2	13	0	0	13	13	46
25	A24	Pumphus	2006-01-02	19:10:56	19:24:37	1.00	2	18	0	0	18	18	46
26	A25	Pumphus	2006-01-02	19:51:33	19:59:59	1.00	2	12	0	0	12	12	46
27	A26	Pumphus	2006-01-02	20:08:15	20:21:45	1.00	2	14	0	0	14	14	46
28	A27	Oljehusbotten	2006-01-02	20:41:26	20:53:25	1.00	2	16	0	0	16	64	16
29	A28	Oljehusbotten	2006-01-02	20:59:59	21:20:18	1.00	2	18	0	0	18	72	16
30	A29	Oljehusbotten	2006-01-03	05:58:12	06:32:35	2.00	2	28	1	3.571429	27	108	16
31	A30	Oljehusbotten	2006-01-03	07:06:22	07:27:13	2.00	2	20	0	0	20	80	16
32	A31	Oljehusbotten	2006-01-03	07:55:49	08:26:08	2.00	2	34	1	2.941176	33	132	16
33	A32	Statorhus	2006-01-03	08:46:00	09:03:51	2.00	2	11	3	27.27273	8	16	94
34	A33	Pumphus	2006-01-03	09:34:25	09:53:39	2.00	2	22	0	0	22	22	54
35	A34	Pumphus	2006-01-03	10:03:10	10:21:00	2.00	2	14	0	0	14	14	54
36	A35	Pumphus	2006-01-03	11:01:17	11:12:24	2.00	2	15	0	0	15	15	54

A.3 Experiment data – General input (run setup and furnace/moulding coordination)

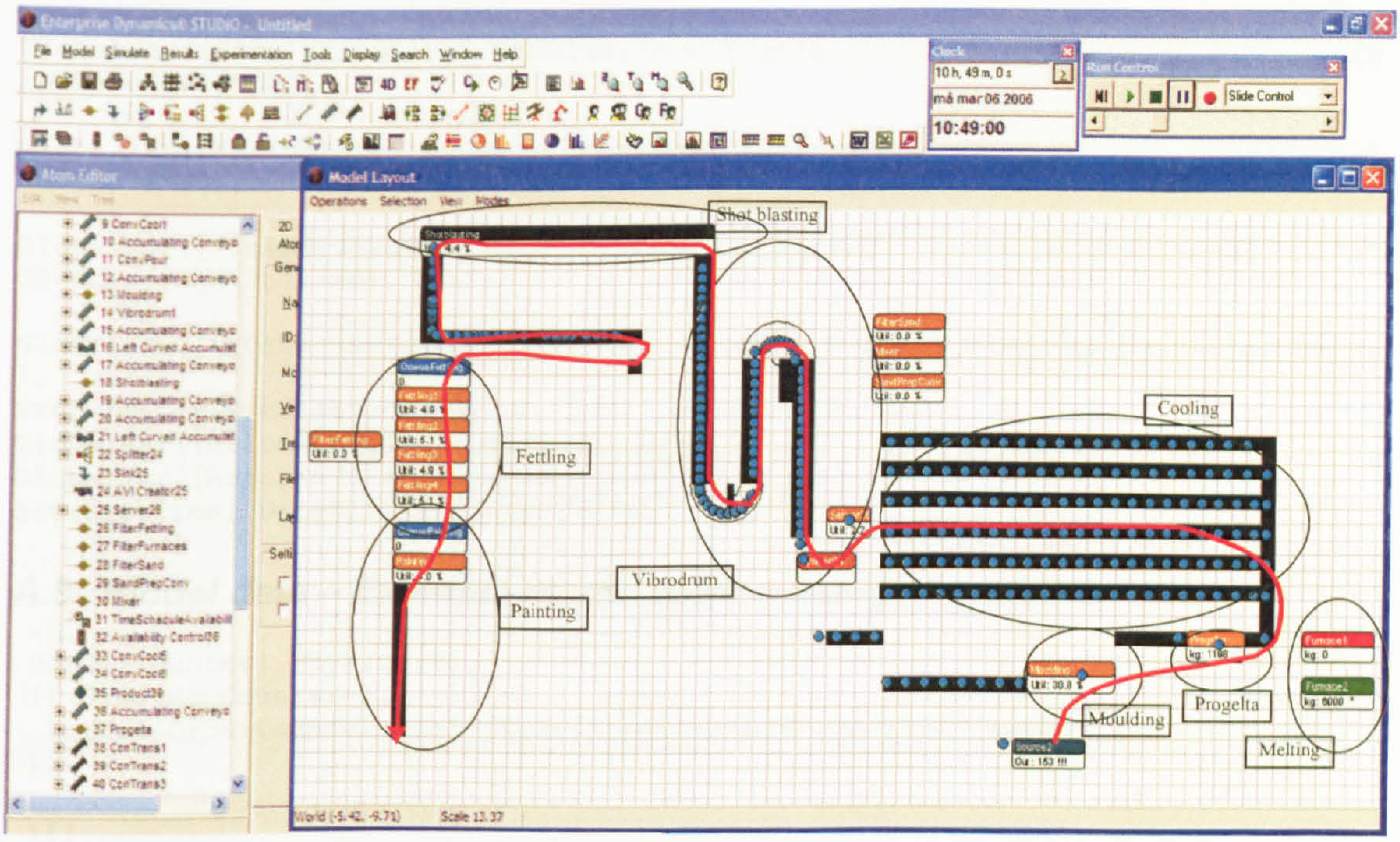
	B	C	D	E	F	G	H	J	K
2	General Input								
4	Simulation time	3	days	0	hours	1	minutes		
5	Warmup time	0	days	0	hours	0	minutes		
7	Time between sampling	0	days	0	hours	30	minutes		
9	Write output?	1	(0=no, 1 =yes)				Run original setup?	0	(1=old, 0=new)
11	Reset before run?	1	(0=no, 1 =yes)						
13	Min time for melting a batch	50	minutes						
15	Min time from full temp until first ladle	10	minutes						
17	Min time for full weight	30	minutes						
19	kWh/ton melting in furnaces	510	kWh/ton						
21	kWh/h holding in furnaces	155	kWh/h						
23	Full furnace	6000	kg						
25	Ladle size	1000	kg						
27	Min Wegith in Progelta before filling up	1500							
29	Max Weight in Progelta	4500							
31	Min Weight in Progelta before stopping	800							
33	Best Weight in Progelta	3500							
35	Time for filling Progelta	4	min						
37	Time before days end for Furnaces to stop	120	min						

A.4 Experiment data – Power use

	Equipment	Status	Choose new distribution!	Distribution	Value1	Value2	Value 3	Value 4	formula (to sim)	Electricity price (öre/kWh)	Tax (öre/kWh)
9	Moulding	Working		Weibull	206.96	7.63			Weibull(206.96,7.63)	40	0.5
10		Idle		lognormal	59.89	0.17			Lognormal(59.89,0.17)	40	0.5
11		Off		gamma	8.96	2.12			Gamma(8.96,2.12)	40	0.5
12	Sand preparation	Working		Weibull	231.13	10.53			Weibull(231.1272,10.5282)	40	0.5
13	and mixer	Idle		Weibull	16.516	12.46			Weibull(16.51582,12.463)	40	0.5
14		Off		uniform	0	0			Uniform(0, 0)	40	0.5
15	Micro	Working		Weibull	101.24	11.34			Weibull(101.2365,11.3362)	40	0.5
16		Idle		Weibull	22.747	3.755			Weibull(22.7472,3.7549)	40	0.5
17		Off		uniform	0	0			Uniform(0, 0)	40	0.5
18	Shot blasting	Working		log-logistic	150.25	98.96			LogLogistic(150.2539,98.9618)	40	0.5
19		Idle		uniform	0	0			Uniform(0, 0)	40	0.5
20		Off		uniform	0	0			Uniform(0, 0)	40	0.5
21	L20 + L40	Working		log-logistic	26.615	12.12			LogLogistic(26.6152,12.11601)	40	0.5
22		Idle		log-logistic	3.1475	11.46			LogLogistic(3.14745,11.46397)	40	0.5
23		Off		log-logistic	3.1475	11.46			LogLogistic(3.14745,11.46397)	40	0.5
24	LFB25+LFB50	Working		Pearson type V	218.57	12.75			PearsonT5(218.5736,12.7456)	40	0.5
25		Idle		log-logistic	1.1128	8.682			LogLogistic(1.1128,8.6822)	40	0.5
26		Off		uniform	1	1			Uniform(1,1)	40	0.5
27	Painting	Working		uniform	151.04	206.1			Uniform(151.042,206.086)	40	0.5
28		Idle		uniform	1	2			Uniform(1,2)	40	0.5
29		Off		uniform	1	2			Uniform(1,2)	40	0.5
30	Sand preparation cor	Working		lognormal	97.07	0.054			LogNormal(97.07031,0.05365)	40	0.5
31		Idle		log-logistic	36.699	36.75			LogLogistic(36.69923,36.75498)	40	0.5
32		Off		uniform	1	1			Uniform(1,1)	40	0.5
33	Vibrodrum	Working		Weibull	59.219	13.98			Weibull(59.21911,13.98361)	40	0.5
34		Idle		log-logistic	24.627	30.91			LogLogistic(24.6274,30.9089)	40	0.5
35		Off		log-logistic	8.6087	0.018			LogLogistic(8.60873,0.01789)	40	0.5
46	Filter fettling	Working		Weibull	67.097	6.616			Weibull(67.09711,6.6162)	40	0.5
47	Filter sandpreparatio	Working		Weibull	146.53	70.4			Weibull(146.5312,70.398)	40	0.5
48	Filter melting	Working		log-logistic	59.508	11.04			LogLogistic(59.50839,11.03942)	40	0.5
49	fettling	Working		log-logistic	13.41	38.22			LogLogistic(13.4099,38.2249)	40	0.5

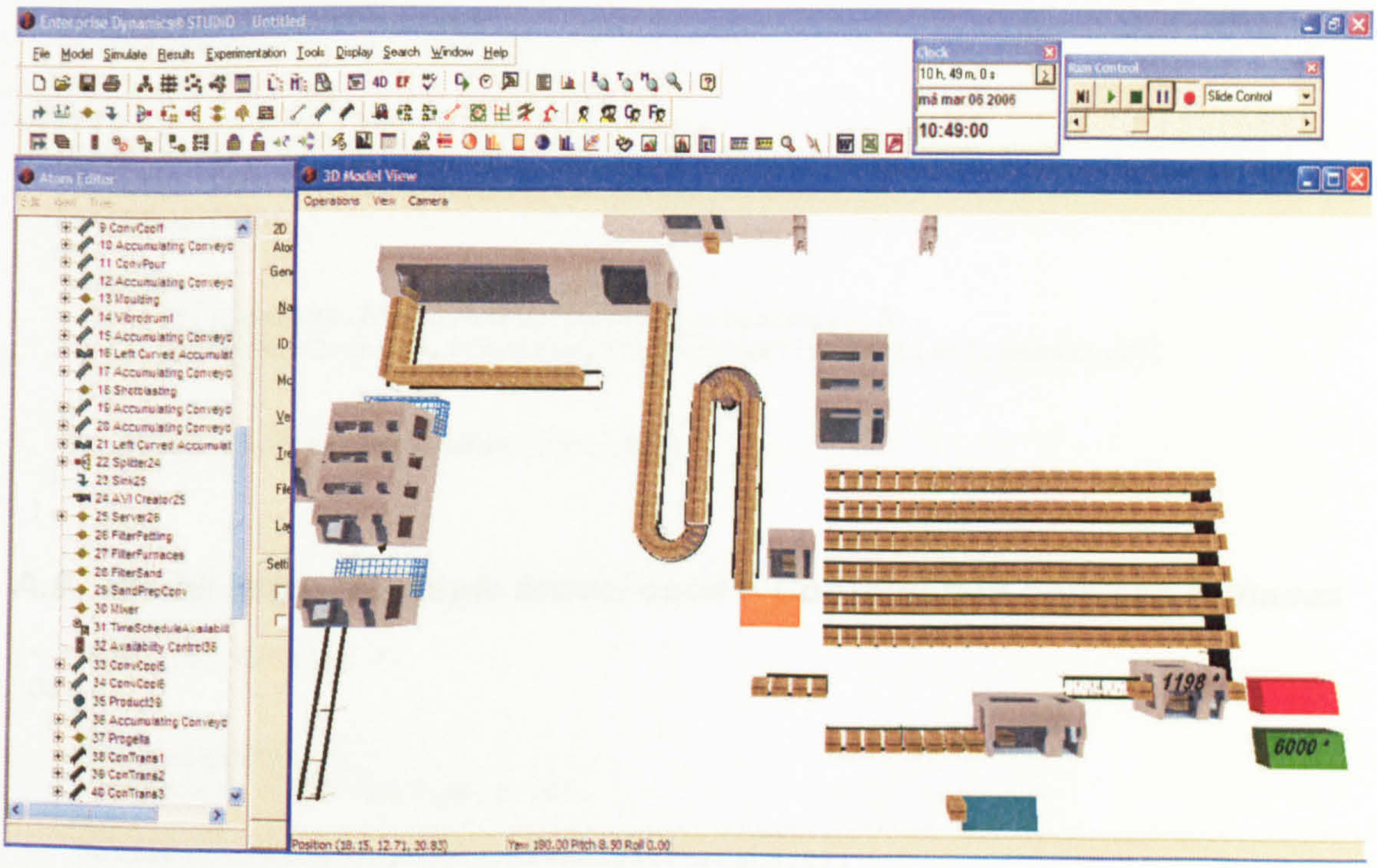
A.5 Model data – 2D view of main parts of the model

The main processes are circled and named. The main flow through the processes is shown with red arrow.



A.6 Model data – 3D view of main parts of the model

The same processes as in A.5 and in the same stage of the simulation run.



A.7 Model data – Example model code - Example of reading data from MS Excel sheets

```
ExcelSheet([GenInput]),

GlobalVar([SimulationTime],vbvalue,ExcelRead(4,3)*86400+ExcelRead(4,5)*3600+Ex
celRead(4,7)*60),

GlobalVar([WarmupTime],vbvalue,ExcelRead(5,3)*86400+ExcelRead(5,5)*3600+ExcelR
ead(5,7)*60),

GlobalVar([TimeBetweenSampling],vbvalue,ExcelRead(7,3)*86400+ExcelRead(7,5)*36
00+ExcelRead(7,7)*60),

GlobalVar([NrOfValuesForMeanSampling],vbvalue,Trunc(TimeBetweenSampling/360)+1
),
StopTime := SimulationTime,
GlobalVar([WriteOut],vbvalue,ExcelRead(9,3)),
GlobalVar([ResetBefore],vbvalue,ExcelRead(11,3)),
Set(BaseTime, DateStr([2006-03-06])),
```

A.8 Model data – Example model code – Assigning orders

```
var([iCounter],VbValue,0),
if(OrderRowCounter=1,
 TotNrInOrderCounter:=cell(1,10,AtomByName([OrderList],model),1)
),

If(
 CurrNrInOrderCounter>TotNrInOrderCounter,
 do(
  CurrNrInOrderCounter:=2,
  inc(OrderRowCounter)
 ),
 Inc(CurrNrInOrderCounter)
),

For(
 iCounter:=1,
 iCounter<=nCols(AtomByName([OrderList],model)),
 inc(iCounter),
 do(
  setLabel(
   Cell(0,iCounter,AtomByName([OrderList],model),2),
   Cell(OrderRowCounter,iCounter,AtomByName([OrderList],model),2),
   i
  ),
  TotNrInOrderCounter:=Label([Moulded],i)
 )
),
```

A.9 Model data – Example model code – Coordination between furnaces

```
{* Event 10: Melting *}
 Do(
  if(
   Furnace2Melting=1,
   CreateEvent(NewEventTime,c,10),
   do(
    SetLabel([CurrentWeight],MaxWeightFurnace,c),
    Inc(NrOfMolts),
    Status(c):=2,
    CreateEvent(MinTimeFullWeight,c,11)
```

```
    )
   )
  ),
  {* Event 11: Full weight *}
  Do(
   CreateEvent(MinTimeMelting-MinTimeFullWeight,c,12)
  ),
   {* Event 12: Testing *}
  Do(
   Status(c):=35,
   CreateEvent(MinTimeTesting,c,13)
  ),
  {* Event 13: Status to Idle*}
  Do(
   Status(c):=1,
   Furnace1Melting:=0,
   Furnace1Avail:=1,
   if(
    NrOfMolts=1,
    do(
     CreateEvent(0,AtomByName([Furnace2],model),10),
     Furnace2Melting:=1,
     Furnace2Avail:=0
    )
   )
  )
```

A.10 Model data – Example model code – Coordination between pouring furnace and melting furnaces

```
{* Event 10: Checks parameters to set input open *}
 Do(
  if(
   and(Content(c)<1,label([CurrentWeight],c)>MinWeightProgeltaStop),
   openallic(c),
   CreateEvent(NewEventTime,c,10)
  )
 ),
 {* Event 11: Gets iron from Furnace1 *}
 Do(
  if(
   Furnace1Melting=0,
   do(
    Inc(Label([CurrentWeight],c),LadleSize),
    Dec(Label([CurrentWeight],AtomByName([Furnace1],model)),LadleSize),
    var([TempW1],vbvalue,MaxWeightProgelta-Label([CurrentWeight],c)),
    If(
     TempW1>Label([CurrentWeight],AtomByName([Furnace1],model)),
     CreateEvent(0,c,13),
     do(
      if(
       Label([CurrentWeight],AtomByName([Furnace1],model))<LadleSize,
       CreateEvent(0,c,13)
      )
     )
    )
   ),
   CreateEvent(NewEventTime,c,11)
  )
 ),

 {* Event 12: Gets iron from Furnace2 *}
 Do(
  if(
```

```
      Furnace2Melting=0,
      do(
       Inc(Label([CurrentWeight],c),LadleSize),
      Dec(Label([CurrentWeight],AtomByName([Furnace2],model)),LadleSize),

      var([TempW2],vbvalue,MaxWeightProgelta-Label([CurrentWeight],c)),
      If(
       TempW2>Label([CurrentWeight],AtomByName([Furnace2],model)),
       CreateEvent(0,c,14),
       do(
        if(
         Label([CurrentWeight],AtomByName([Furnace2],model))<LadleSize,
         CreateEvent(0,c,14)
        )
       )
      )
     ),
     CreateEvent(NewEventTime,c,12)
    )
   ),

   {* Event 13: Gets all iron left from Furnace1 *}
   Do(

  Inc(Label([CurrentWeight],c),Label([CurrentWeight],AtomByName([Furnace1],model
  ))),

  Dec(Label([CurrentWeight],AtomByName([Furnace1],model)),Label([CurrentWeight],
  AtomByName([Furnace1],model))),
    Status(AtomByName([Furnace1],model)):=3,
    FurnaceCurrent:=2,
    if(
     Furnace2Melting=0,
     do(
      if(RunOriginalSetup=1,
       do(
        CreateEvent(0,AtomByName([Furnace1],model),10),
        Furnace1Melting:=1,
        Furnace1Avail:=0
       ),
       do(

  if(CheckIfNewFurnaceNeeded(MinWeightBeforeFillProgelta,OrderRowCounter,CurrNrI
  nOrderCounter,TotNrInOrderCounter,MinTimeMelting)=1,
         do(
          CreateEvent(0,AtomByName([Furnace1],model),10),
          Furnace1Melting:=1,
          Furnace1Avail:=0
         ),
         CreateEvent(NewEventTime2,c,15)
        )
       )
      )
     ),
     CreateEvent(NewEventTime,c,13)
    )
   ),

   {* Event 14: Gets all iron left from Furnace2 *}
   Do(

  Inc(Label([CurrentWeight],c),Label([CurrentWeight],AtomByName([Furnace2],model
  ))),
```

```
Dec(Label([CurrentWeight],AtomByName([Furnace2],model)),Label([CurrentWeight],
AtomByName([Furnace2],model))),
  Status(AtomByName([Furnace2],model)):=3,
  FurnaceCurrent:=1,
  if(
   Furnace1Melting=0,
   do(
    if(RunOriginalSetup=1,
     do(
      CreateEvent(0,AtomByName([Furnace2],model),10),
      Furnace2Melting:=1,
      Furnace2Avail:=0
     ),
     do(

if(CheckIfNewFurnaceNeeded(MinWeightBeforeFillProgelta,OrderRowCounter,CurrNrI
nOrderCounter,TotNrInOrderCounter,MinTimeMelting)=1,
       do(
        CreateEvent(0,AtomByName([Furnace2],model),10),
        Furnace2Melting:=1,
        Furnace2Avail:=0
       ),
       CreateEvent(NewEventTime2,c,16)
      )
     )
    )
   ),
   CreateEvent(NewEventTime,c,14)
  )
 ),
 {* Event 15: Furnace1 repeat *}
do(

if(CheckIfNewFurnaceNeeded(MinWeightBeforeFillProgelta,OrderRowCounter,CurrNrI
nOrderCounter,TotNrInOrderCounter,MinTimeMelting)=1,
      do(
       CreateEvent(0,AtomByName([Furnace1],model),10),
       Furnace1Melting:=1,
       Furnace1Avail:=0
      ),
      CreateEvent(NewEventTime2,c,15)
     )
),

{* Event 16: Furnace2 repeat *}
do(

if(CheckIfNewFurnaceNeeded(MinWeightBeforeFillProgelta,OrderRowCounter,CurrNrI
nOrderCounter,TotNrInOrderCounter,MinTimeMelting)=1,
      do(
       CreateEvent(0,AtomByName([Furnace2],model),10),
       Furnace2Melting:=1,
       Furnace2Avail:=0
      ),
      CreateEvent(NewEventTime2,c,16)
     )
)
```

A.11 Model data – Example model code – Writing data to tables for all processes

```
{* Event 10: Write to table every time step*   }
 Do(
```

```
Var([ForVar1],vbvalue,0),
for(
 ForVar1:=1,
 ForVar1<=NrOfProcesses,
 inc(ForVar1),
 do(
  case(
   ForVar1,
   do(
    var([NameEquip],vbstring,[Moulding]),
    var([NameEquipSh],vbstring,[MouldingOut])
   ),
   do(
    var([NameEquip],vbstring,[Vibrodrum1]),
    var([NameEquipSh],vbstring,[VibrodrumOut])
   ),
   do(
    var([NameEquip],vbstring,[Shotblasting]),
    var([NameEquipSh],vbstring,[ShotblastingOut])
   ),
   do(
    var([NameEquip],vbstring,[FilterFettling]),
    var([NameEquipSh],vbstring,[FilterFettlingOut])
   ),
   do(
    var([NameEquip],vbstring,[FilterFurnaces]),
    var([NameEquipSh],vbstring,[FilterFurnacesOut])
   ),
   do(
    var([NameEquip],vbstring,[FilterSand]),
    var([NameEquipSh],vbstring,[FilterSandOut])
   ),
   do(
    var([NameEquip],vbstring,[SandPrepConv]),
    var([NameEquipSh],vbstring,[SandPrepConvOut])
   ),
   do(
    var([NameEquip],vbstring,[Mixer]),
    var([NameEquipSh],vbstring,[MixerOut])
   ),
   do(
    var([NameEquip],vbstring,[Progelta]),
    var([NameEquipSh],vbstring,[ProgeltaOut])
   ),
   do(
    var([NameEquip],vbstring,[Furnace1]),
    var([NameEquipSh],vbstring,[Furnace1Out])
   ),
   do(
    var([NameEquip],vbstring,[Furnace2]),
    var([NameEquipSh],vbstring,[Furnace2Out])
   ),
   do(
    var([NameEquip],vbstring,[Painting]),
    var([NameEquipSh],vbstring,[PaintingOut])
   )
  ),
ProgressBar(1, 1, 1, concat([Calculating ],NameEquipSh, [ data])),
var([IDEquip],vbvalue,atomID(atombyname(NameEquip,model))),
var([ForVar],vbvalue,0),
CounterRow:=1,
For(
 ForVar:=1,
 ForVar<(SimulationTime/TimeBetweenSampling),
 Inc(ForVar),
```

```
do(
 CounterCol:=1,
 var([typ],vbvalue,1),
 For(typ:=1,
  typ<=32,
  inc(typ),
  do(

SetCell(CounterRow,CounterCol,TimeForStatus(AtomByID(IDEquip,model),typ,(ForVa
r-
1)*TimeBetweenSampling,ForVar*TimeBetweenSampling),AtomByID(IDEquip,model),1),
   Inc(CounterCol)
  )
 ),
{33}SetCell(CounterRow,CounterCol,ForVar*TimeBetweenSampling,AtomByID(IDEquip,
model),1),   {Time}
 Inc(CounterCol),
{34}SetCell(CounterRow,CounterCol,TimeBetweenSampling,AtomByID(IDEquip,model),
1),    {TimeSinceLast}
 Inc(CounterCol),

{33alt}var([extra],vbvalue,TimeForStatus(AtomByID(IDEquip,model),33,(ForVar-
1)*TimeBetweenSampling,ForVar*TimeBetweenSampling)),

{35}SetCell(CounterRow,CounterCol,

cell(CounterRow,2)+cell(CounterRow,6)+cell(CounterRow,7)+cell(CounterRow,8)+ce
ll(CounterRow,9)+
   cell(CounterRow,26)+cell(CounterRow,29),
   AtomByID(IDEquip,model),1),
  Inc(CounterCol),

{36}SetCell(CounterRow,CounterCol,

cell(CounterRow,1)+cell(CounterRow,4)+cell(CounterRow,5)+cell(CounterRow,10)+c
ell(CounterRow,11)+

cell(CounterRow,13)+cell(CounterRow,14)+cell(CounterRow,15)+cell(CounterRow,16
)+cell(CounterRow,17)+

cell(CounterRow,18)+cell(CounterRow,19)+cell(CounterRow,20)+cell(CounterRow,21
)+cell(CounterRow,22)+

cell(CounterRow,23)+cell(CounterRow,24)+cell(CounterRow,25)+cell(CounterRow,27
)+cell(CounterRow,28)+
   cell(CounterRow,30)+cell(CounterRow,31)+cell(CounterRow,32)+extra,
   AtomByID(IDEquip,model),1),
  Inc(CounterCol),

{37}SetCell(CounterRow,CounterCol,
   cell(CounterRow,3)+cell(CounterRow,12),
   AtomByID(IDEquip,model),1),
  Inc(CounterCol),

  var([TempEnergy],vbvalue,0),
  var([TempEnergyCounter],vbvalue,0),
  for(
   TempEnergyCounter:=1,
   TempEnergyCounter<=NrOfValuesForMeanSampling,
   Inc(TempEnergyCounter),

TempEnergy:=TempEnergy+round((cell(CounterRow,35)*FGetNewValueFromDist(Name(at
ombyID(IDEquip,model)),[Work])+
```

```
cell(CounterRow,36)*FGetNewValueFromDist(Name(atombyID(IDEquip,model)),[Idle])
+

cell(CounterRow,37)*FGetNewValueFromDist(Name(atombyID(IDEquip,model)),[Off]))
/TimeBetweenSampling)
    ),
    TempEnergy:=TempEnergy/NrOfValuesForMeanSampling,

{38}SetCell(CounterRow,CounterCol,      {Power}
     TempEnergy,
     AtomByID(IDEquip,model),1),
    Inc(CounterCol),

{39}If(CounterRow=1,       {EnergyAcc}
     SetCell(CounterRow,CounterCol,cell(CounterRow,CounterCol-
1)/3600*TimeBetweenSampling,AtomByID(IDEquip,model),1),
     SetCell(CounterRow,CounterCol,cell(CounterRow,CounterCol-
1)/3600*TimeBetweenSampling+cell(CounterRow-1,CounterCol),
     AtomByID(IDEquip,model),1)
    ),
    Inc(CounterCol),

{End of writing}

    if(   {Increase table size}
     Mod(CounterRow,nRows(AtomByID(IDEquip,model)))=0,
     SetTable(nRows(AtomByID(IDEquip,model))*2,nCols(AtomByID(IDEquip,model)))
    ),
    Inc(CounterRow)
  )
 ),
 ProgressBar(1, 1, 1, concat([Printing to Excel ],NameEquipSh, [ data])),
 FuncWriteExcel(CounterRow-1,CounterCol-32,IDEquip,NameEquipSh)
 )
 ),
 ProgressBar(0)
),
```

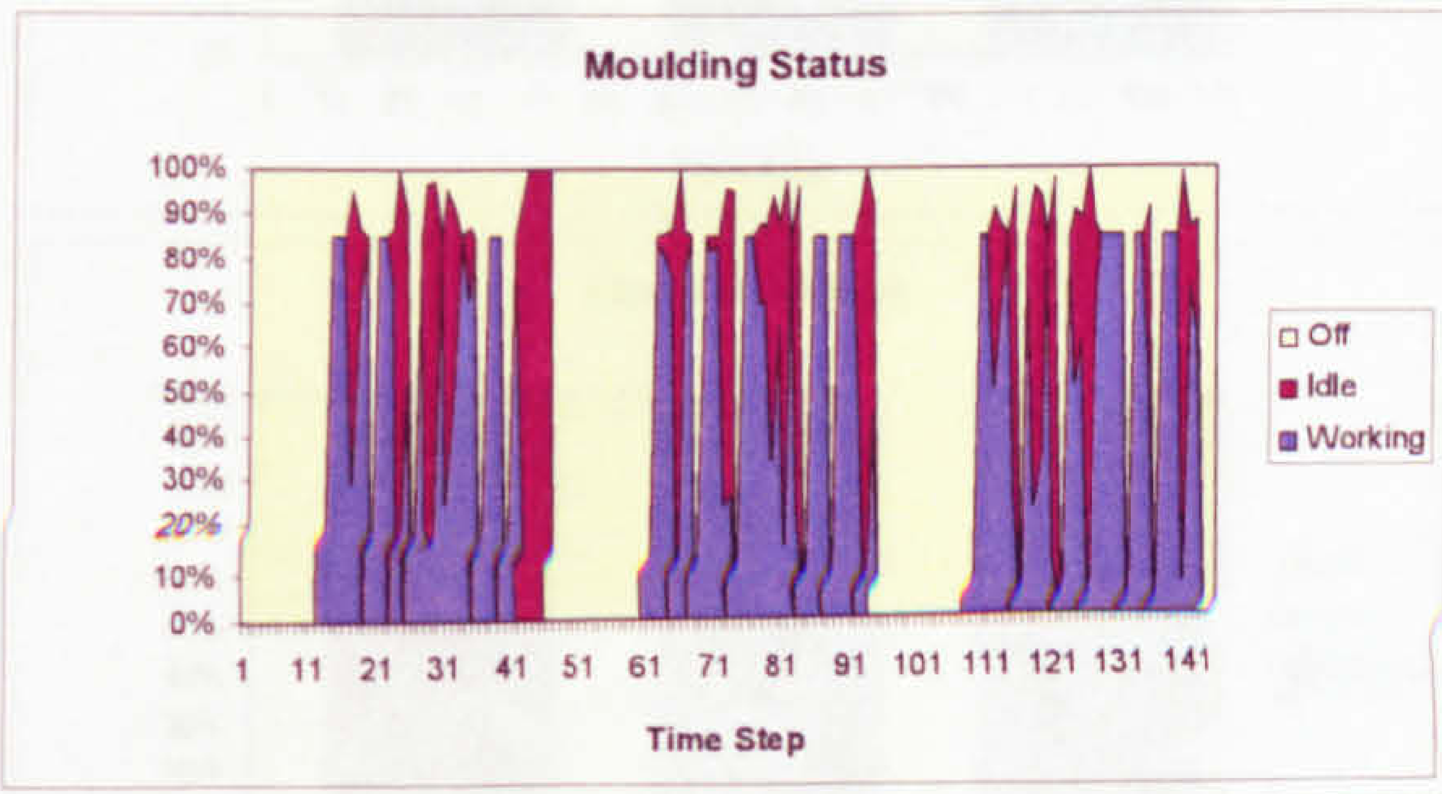
A.12 Output data – Time in states, mean power use and accumulated energy use

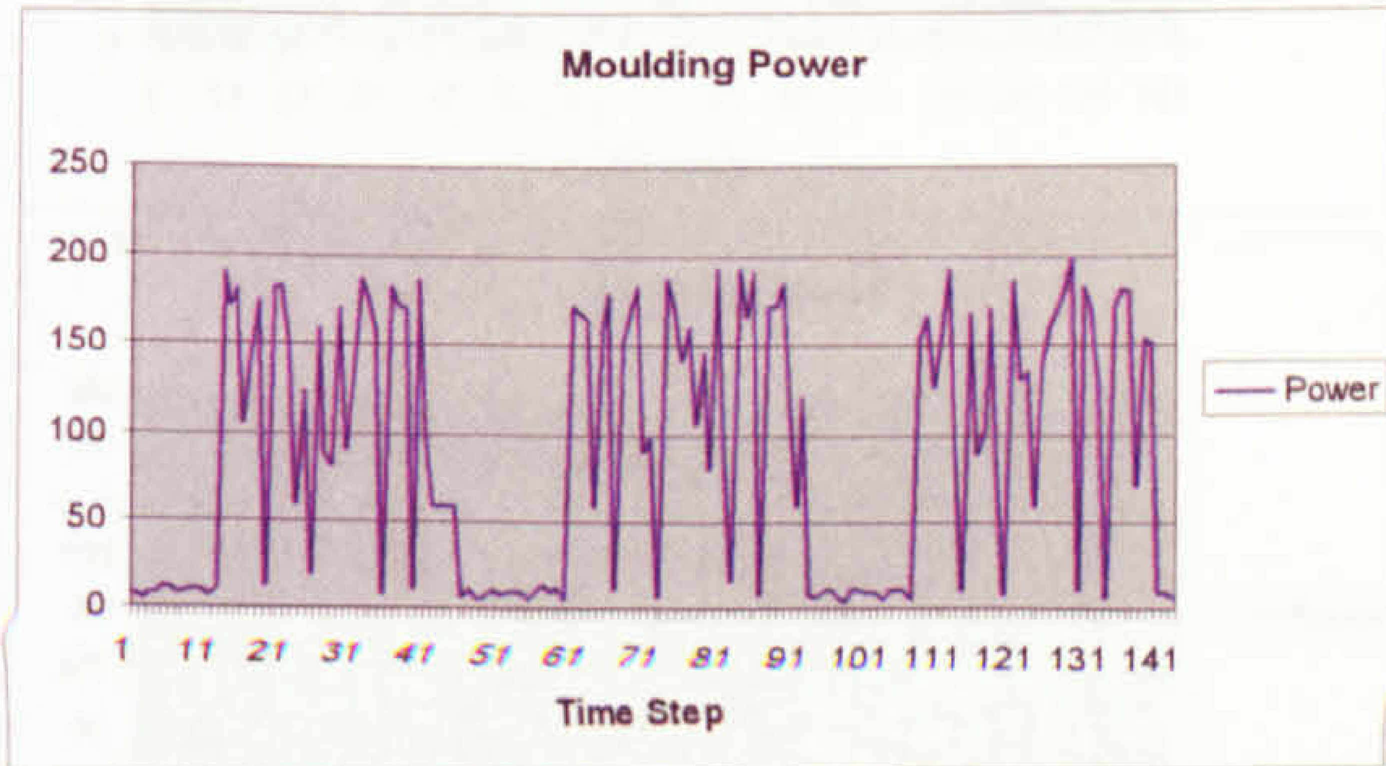
Every process generates a similar output sheet with time in different states, mean power use and accumulated energy use.

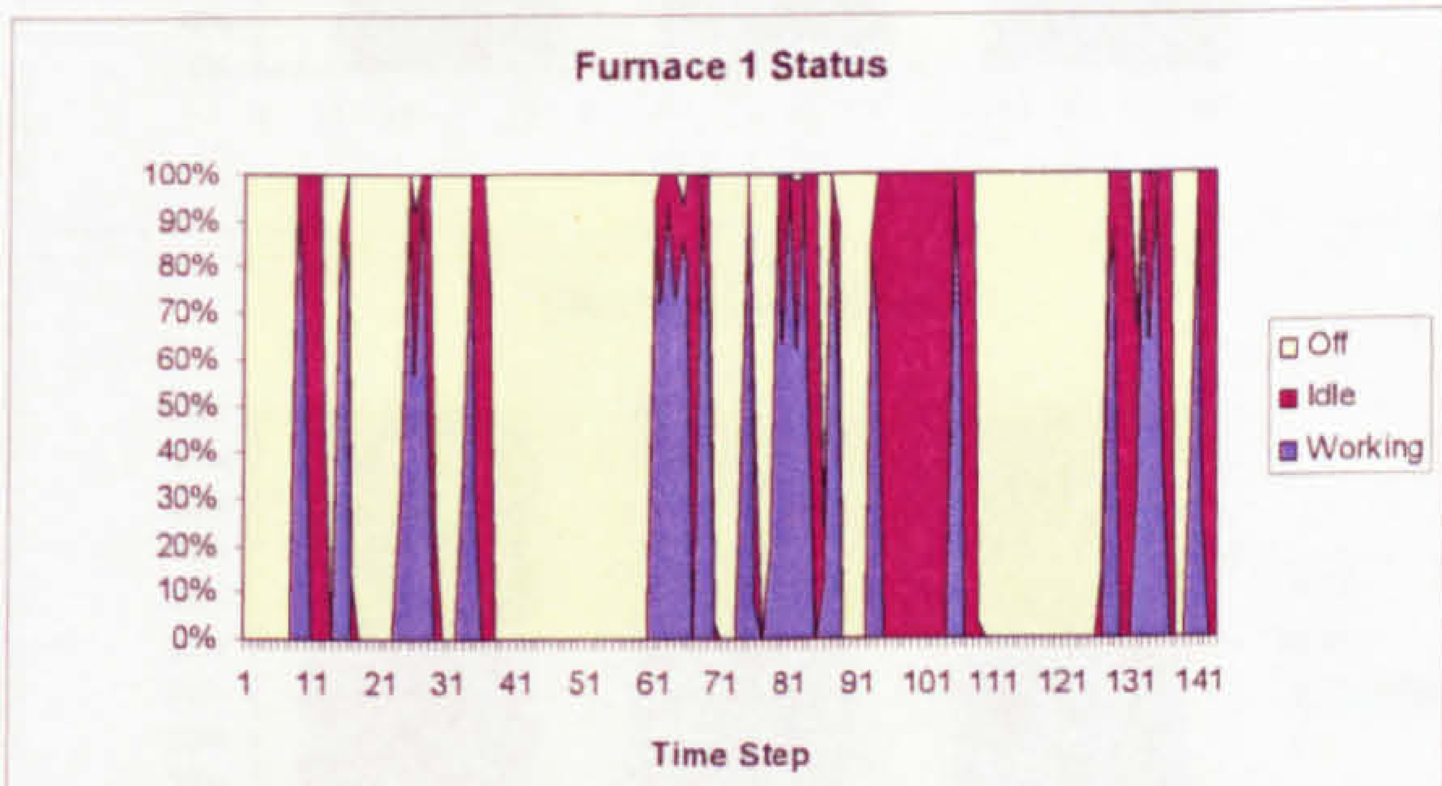
	A	B	C	D	E	F	G
1	Time	TimeSinceLast	Working	Idle	Off	Power	EnergyAcc
2	1800	1800	0	0	1800	8.833333333	4.416666667
3	3600	1800	0	0	1800	5.166666667	7
4	5400	1800	0	0	1800	7.666666667	10.83333333
5	7200	1800	0	0	1800	7.666666667	14.66666667
6	9000	1800	0	0	1800	12.5	20.91666667
7	10800	1800	0	0	1800	11.66666667	26.75
8	12600	1800	0	0	1800	7.666666667	30.58333333
9	14400	1800	0	0	1800	9.333333333	35.25
10	16200	1800	0	0	1800	10.83333333	40.66666667
11	18000	1800	0	0	1800	10	45.66666667
12	19800	1800	0	0	1800	6.333333333	48.83333333
13	21600	1800	0	0	1800	11.66666667	54.66666667
14	23400	1800	1530	0	270	191.1666667	150.25
15	25200	1800	1530	0	270	172	236.25
16	27000	1800	1530	0	270	182.6666667	327.5833333
17	28800	1800	529.105404	1178.8946	92	105.5	380.3333333
18	30600	1800	1309.49759	258.502407	232	147.1666667	453.9166667
19	32400	1800	1530	0	270	175.3333333	541.5833333
20	34200	1800	0	0	1800	12	547.5833333
21	36000	1800	1530	0	270	183	639.0833333
22	37800	1800	1530	0	270	183.8333333	731
23	39600	1800	1337.87478	226.125224	236	152.6666667	807.3333333
24	41400	1800	0	1800	0	59.83333333	837.25
25	43200	1800	937.522226	697.983575	164.4942	124.3333333	899.4166667
26	45000	1800	0	0	1800	18.66666667	908.75
27	46800	1800	1454.53124	87.9629565	257.5058	160.6666667	989.0833333
28	48600	1800	350.05348	1387.94652	62	89.83333333	1034
29	50400	1800	272.200839	1479.79916	48	81.33333333	1074.666667
30	52200	1800	1530	0	270	170.8333333	1160.083333
31	54000	1800	440.872277	1281.12772	78	91	1205.583333
32	55800	1800	910.836714	729.163286	160	134.1666667	1272.666667
33	57600	1800	1530	0	270	187.6666667	1366.5
34	59400	1800	1274.83878	300.882625	224.2786	176.5	1454.75
35	61200	1800	1530	0	270	159.3333333	1534.416667
36	63000	1800	0	0	1800	8	1538.416667
37	64800	1800	1530	0	270	183.8333333	1630.333333
38	66600	1800	1530	0	270	172.6666667	1716.666667
39	68400	1800	1530	0	270	170.6666667	1802
40	70200	1800	0	0	1800	10.83333333	1807.416667
41	72000	1800	1530	0	270	187	1900.916667
42	73800	1800	595.201742	1099.07685	105.7214	99.66666667	1950.75
43	75600	1800	0	1800	0	60	1980.75
44	77400	1800	0	1800	0	60	2010.75
45	79200	1800	0	1800	0	60	2040.75
46	81000	1800	0	1800	0	60	2070.75
47	82800	1800	0	0	1800	7.5	2074.5

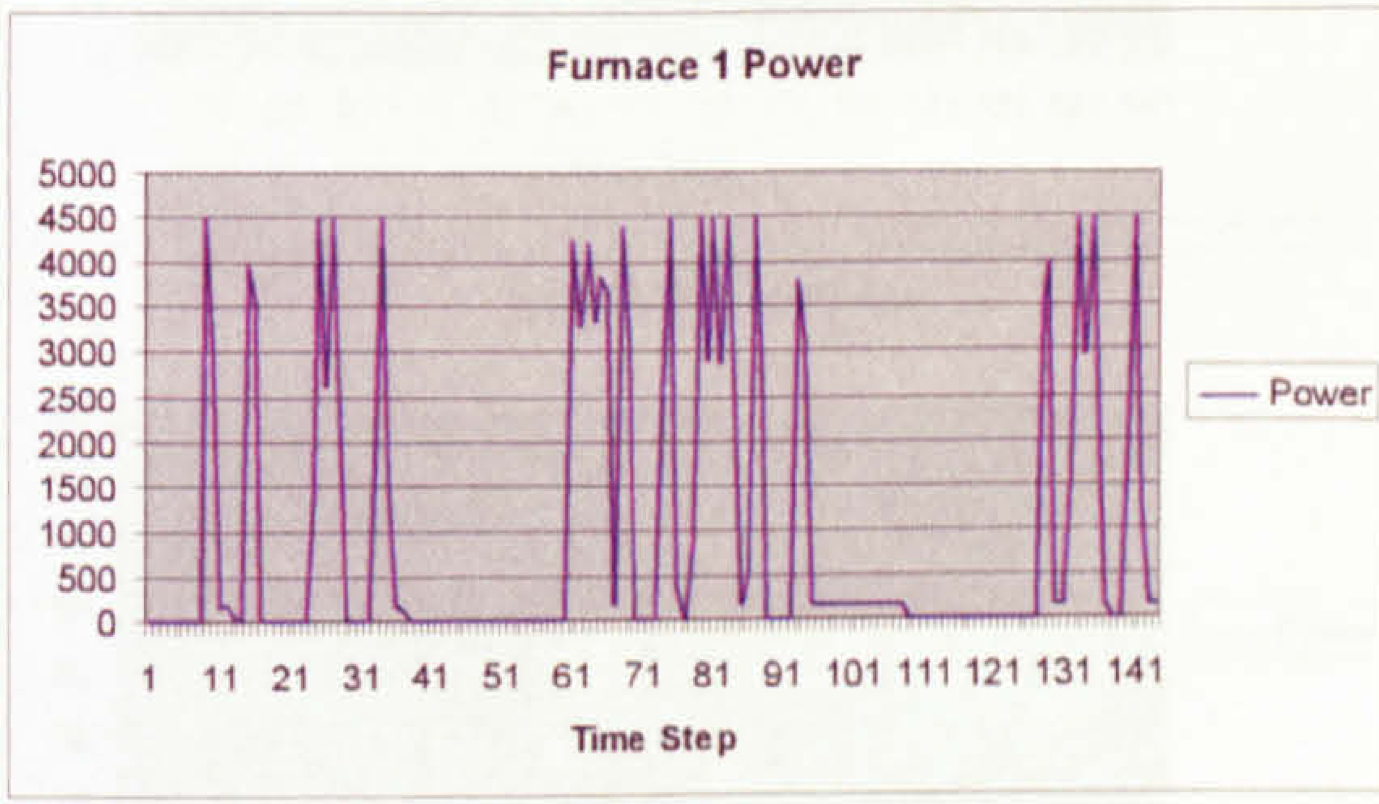
A.13 Output data – Example of energy graphs

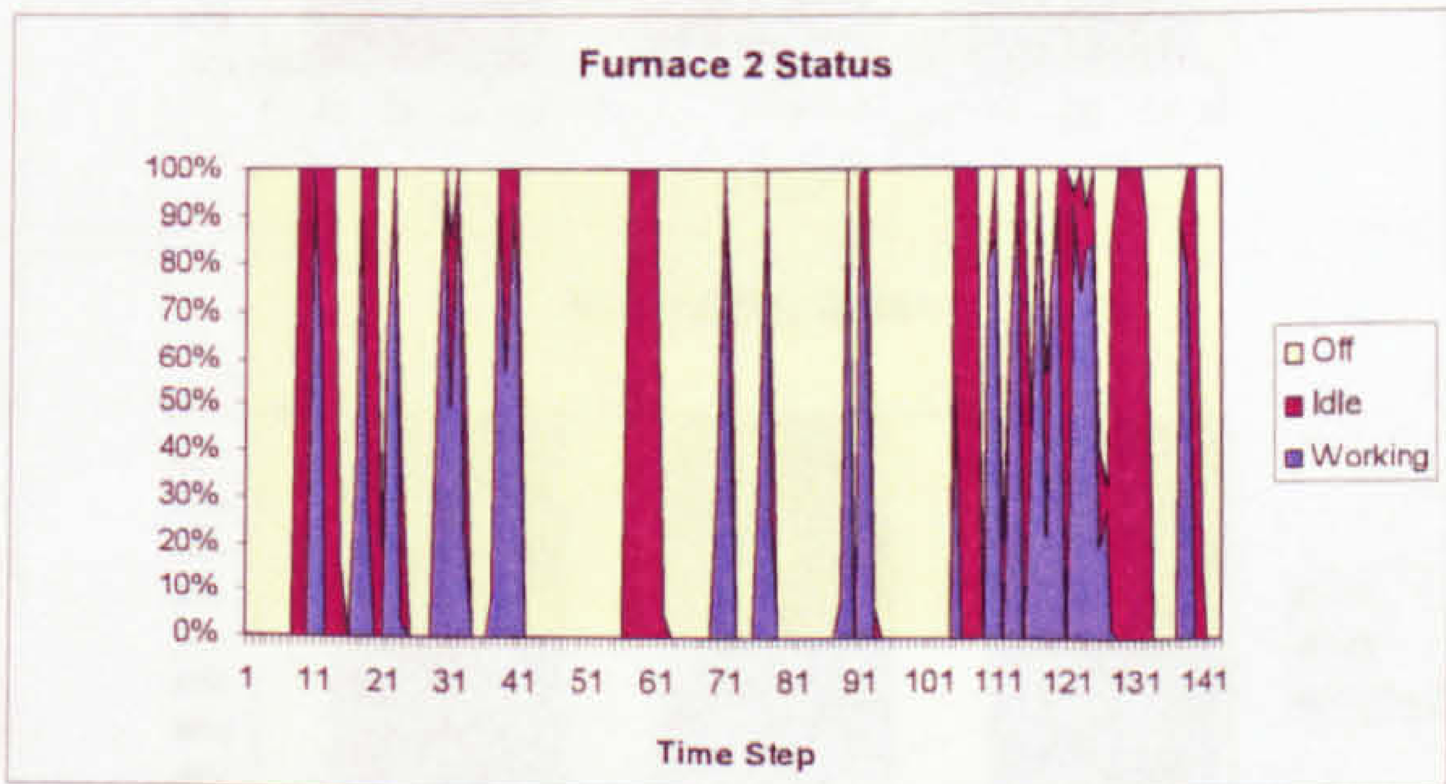
The graphs are based on the output data presented in A.12 and are based on a simulation run for three full work days. Every process generates two graphs – time for each status during each sampling interval and mean power use during each sampling interval. The pouring furnace (Progelta) uses LPG and does not affect the electrical power use.

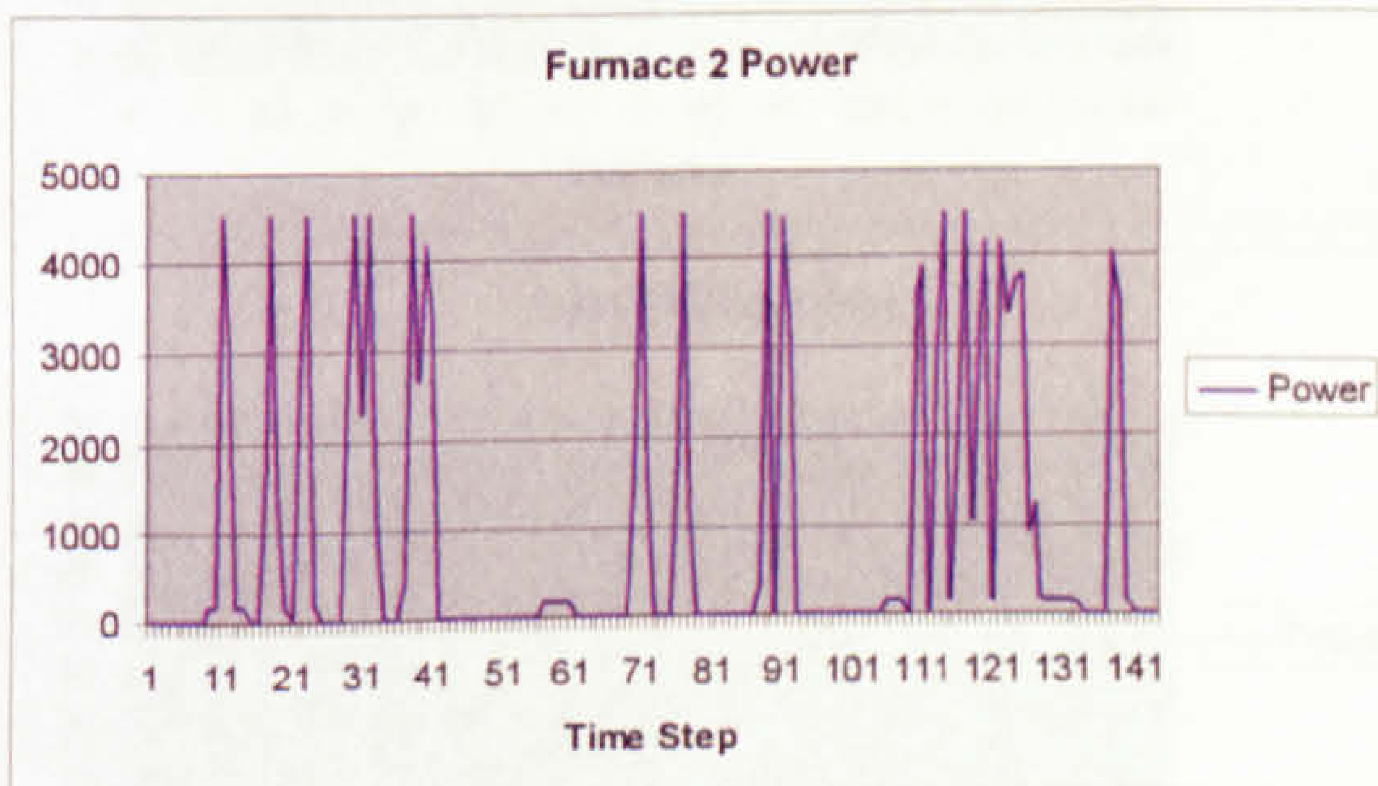


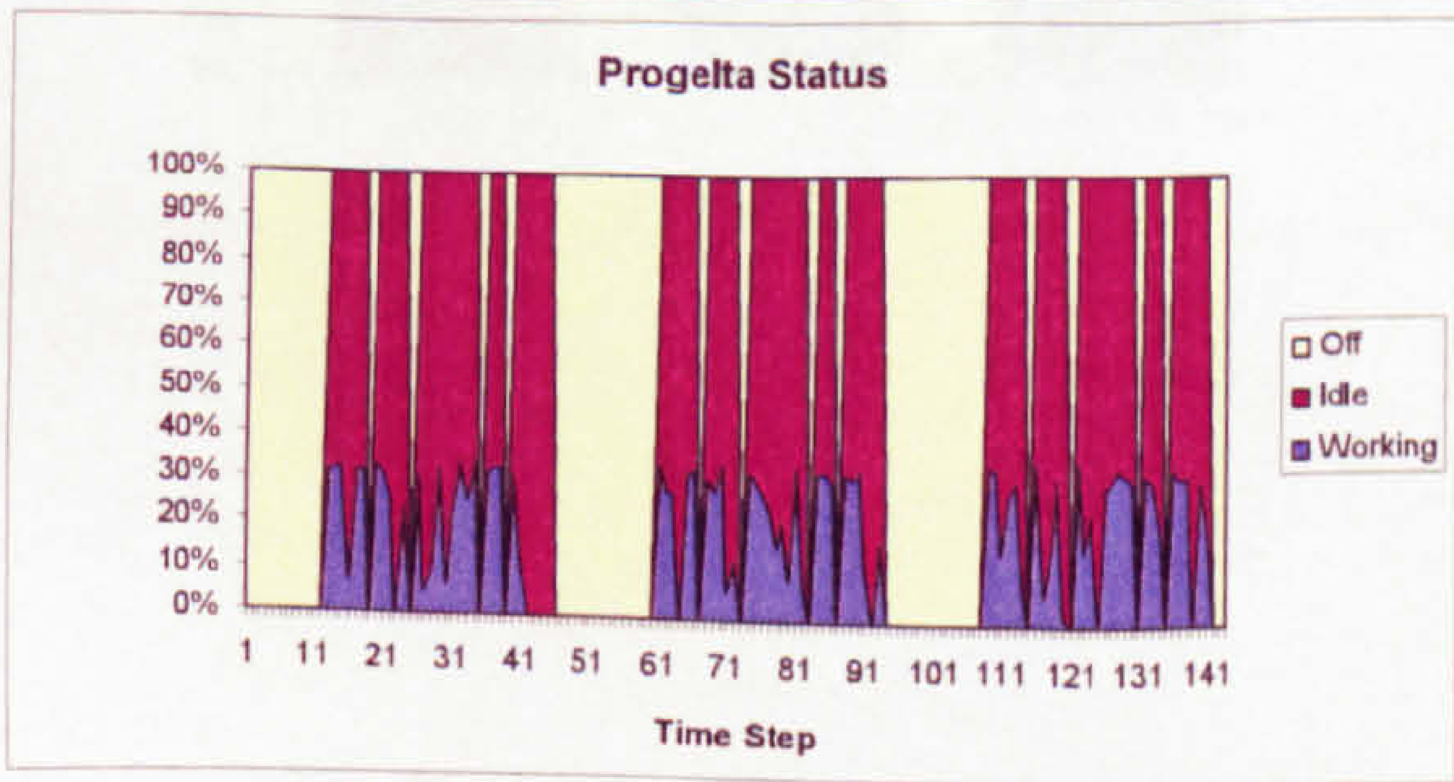


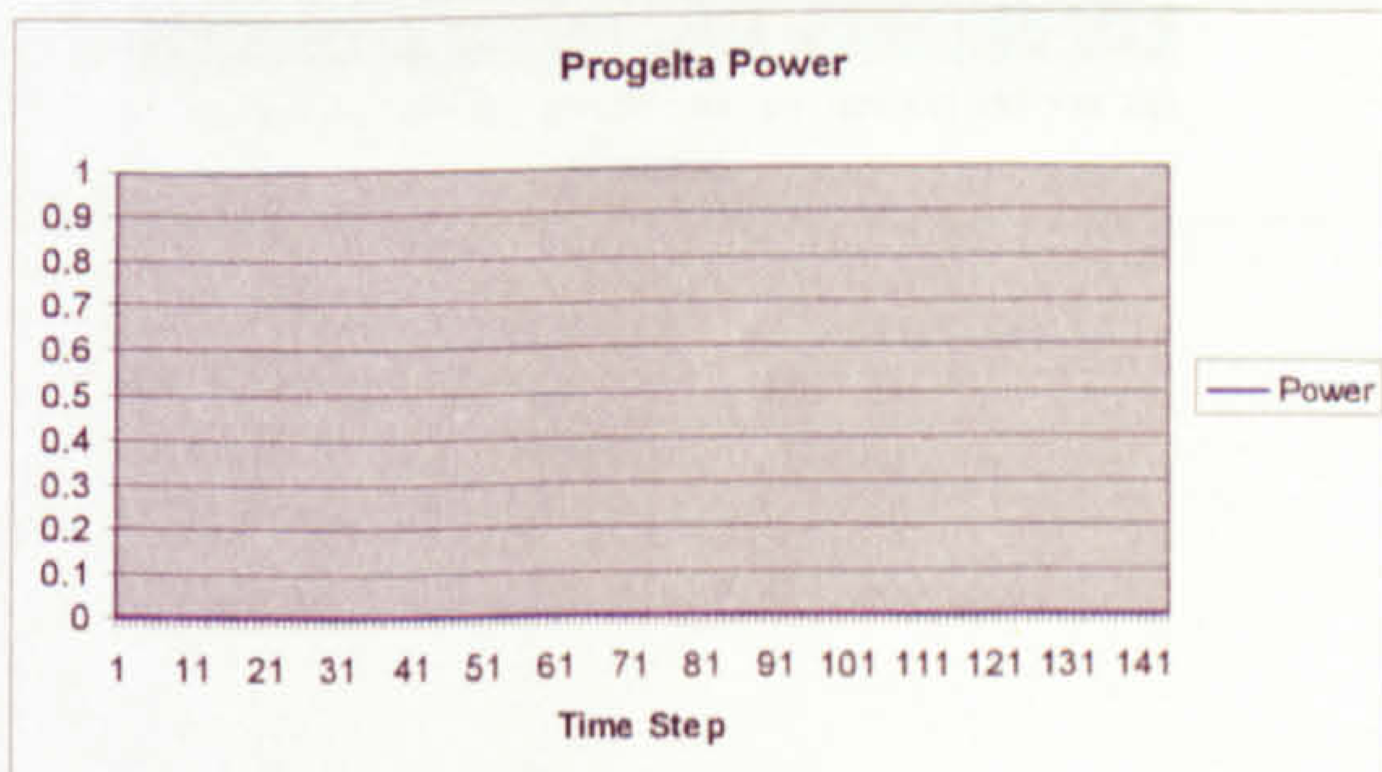


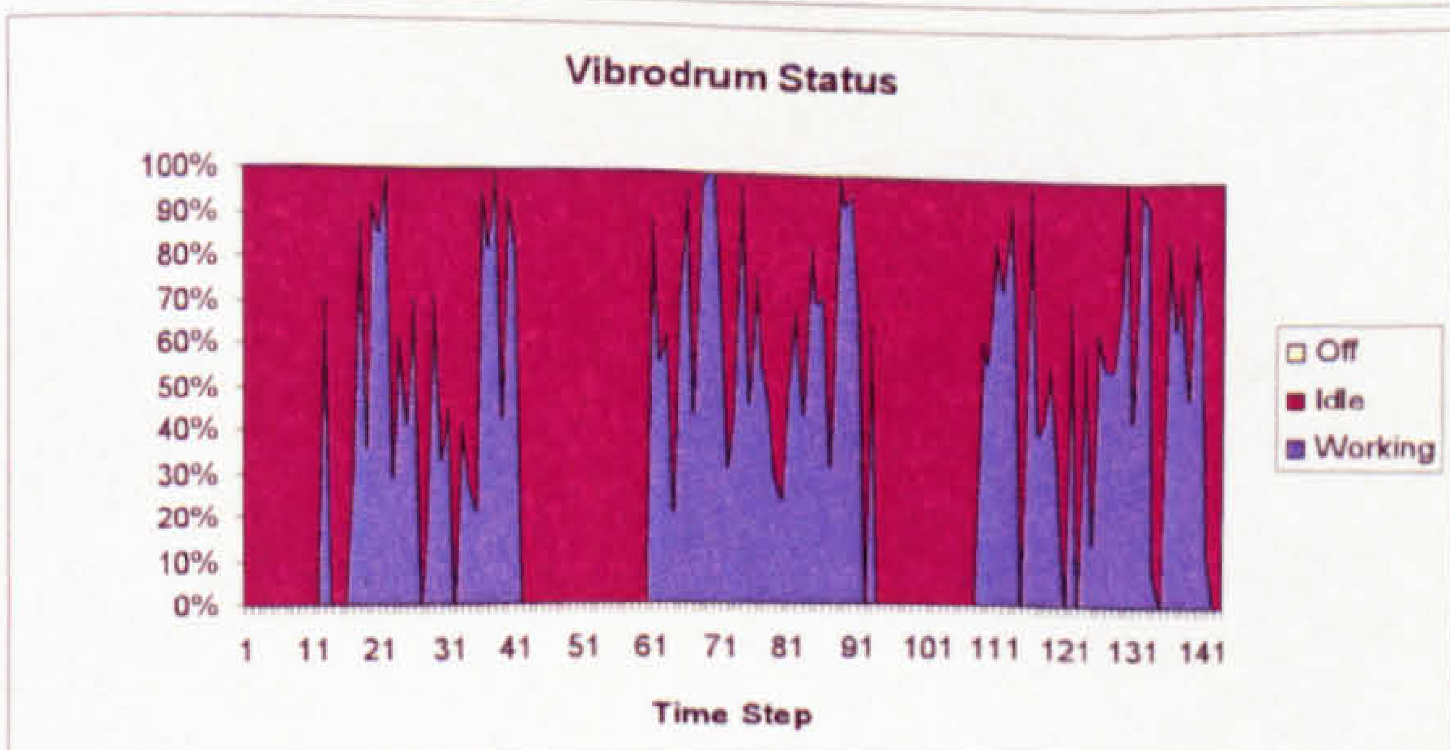


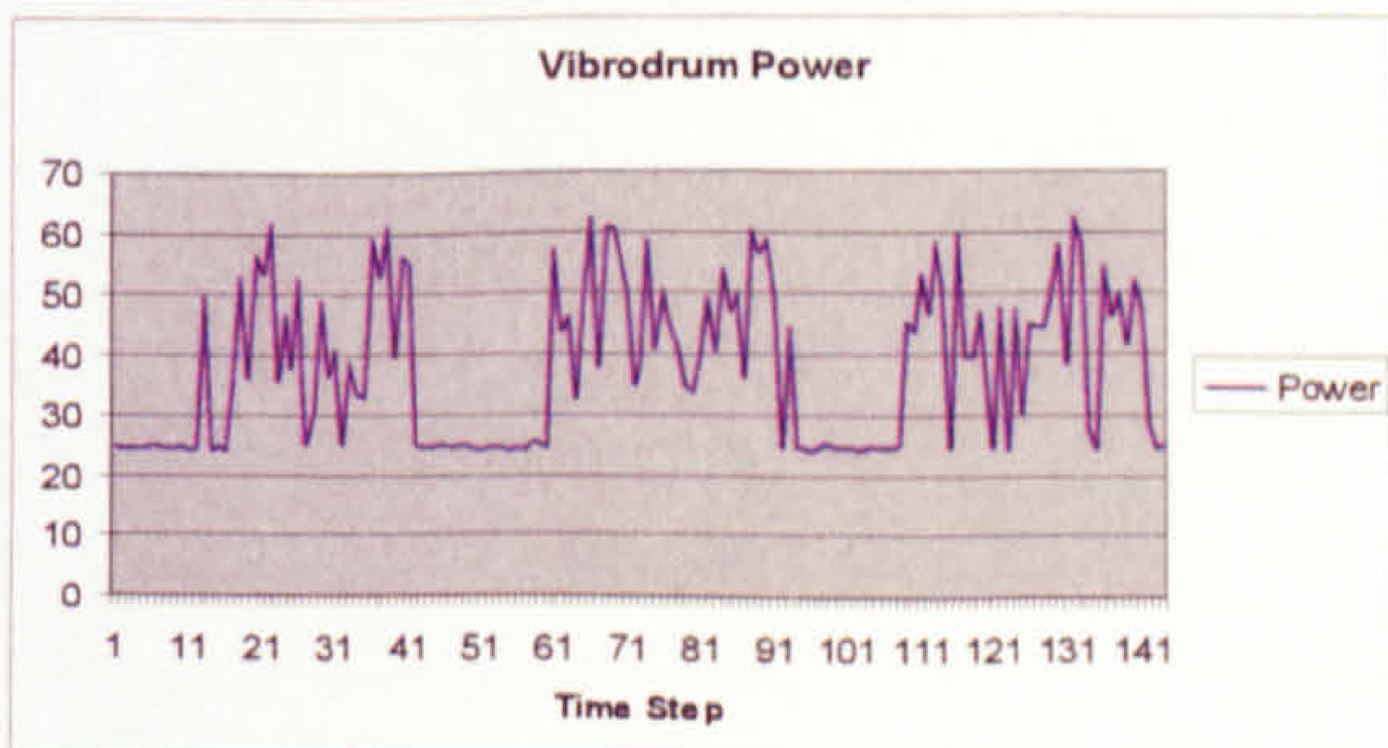


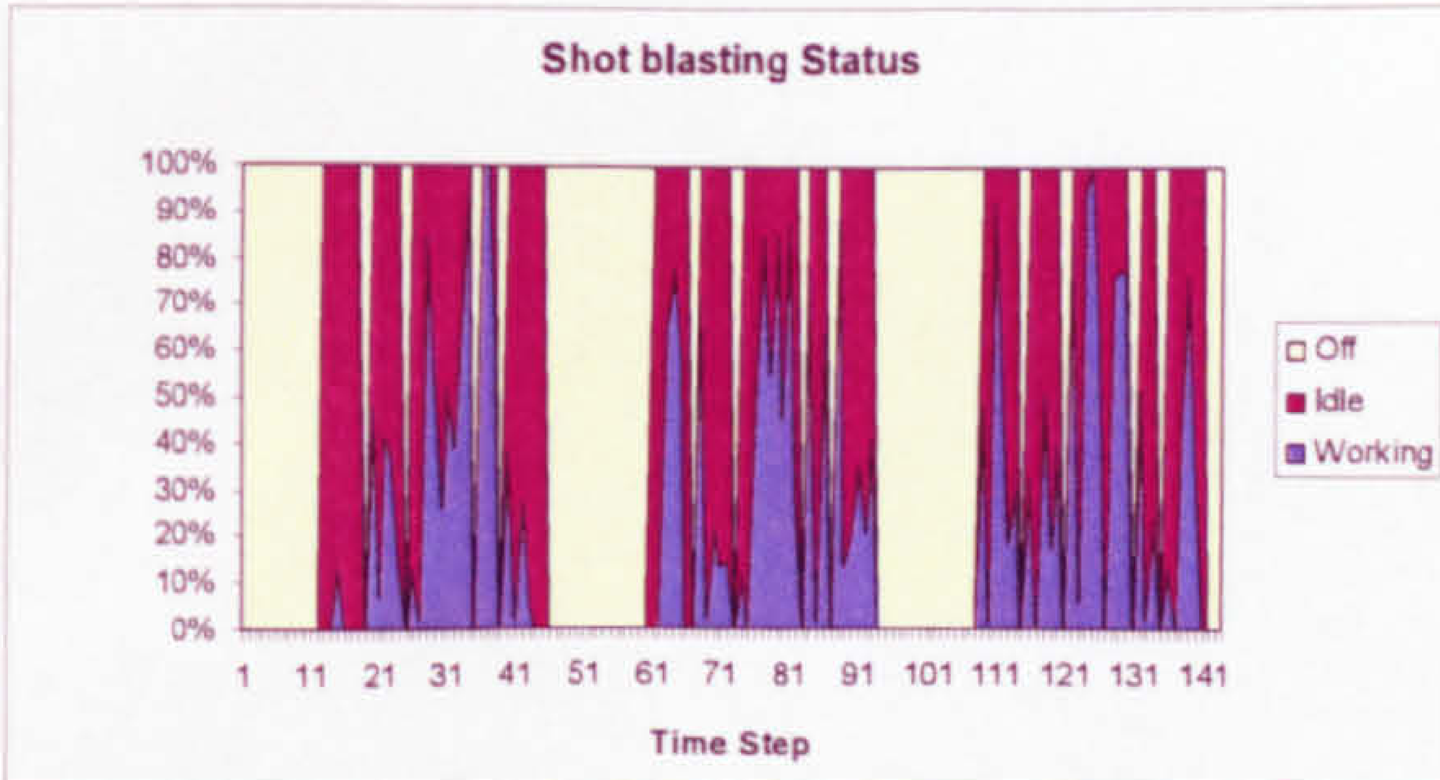


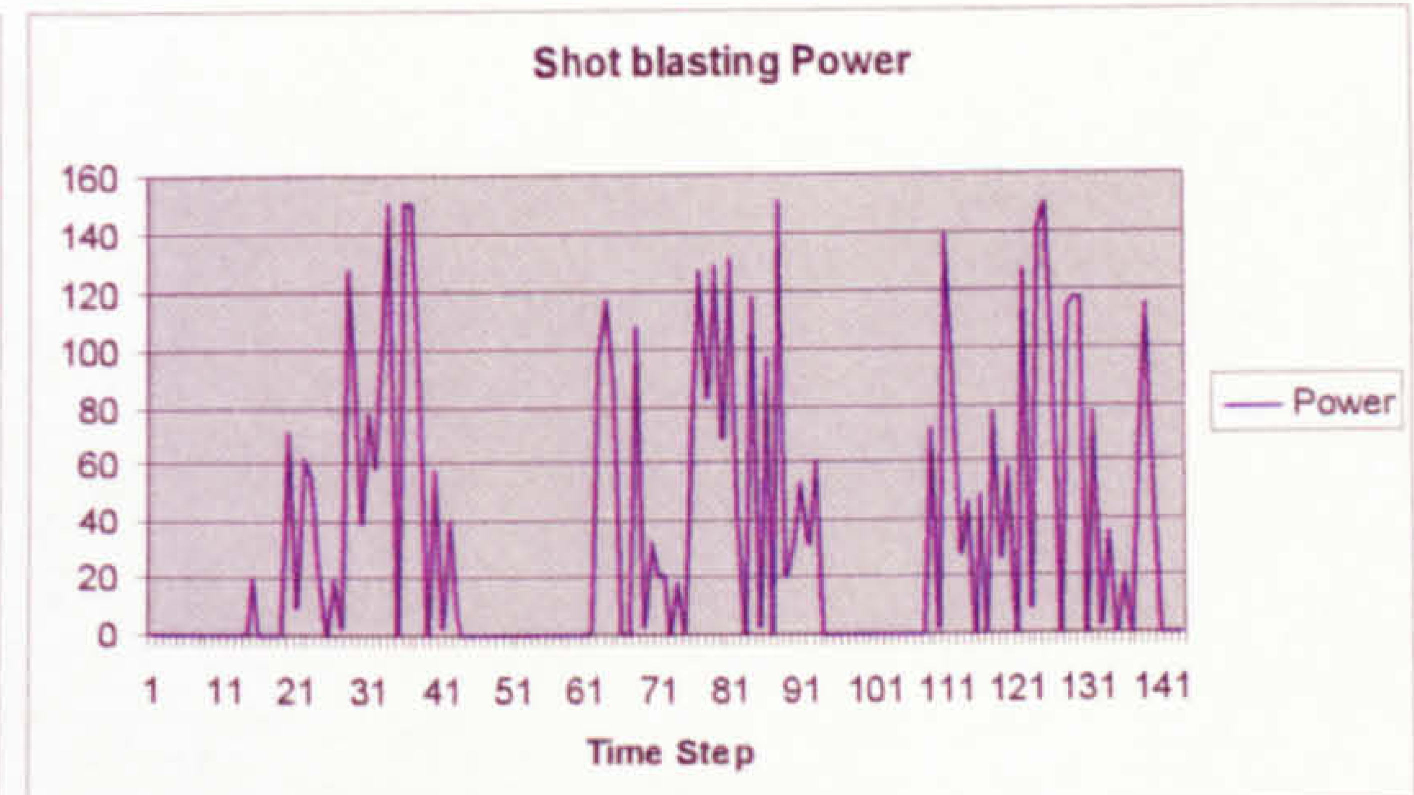


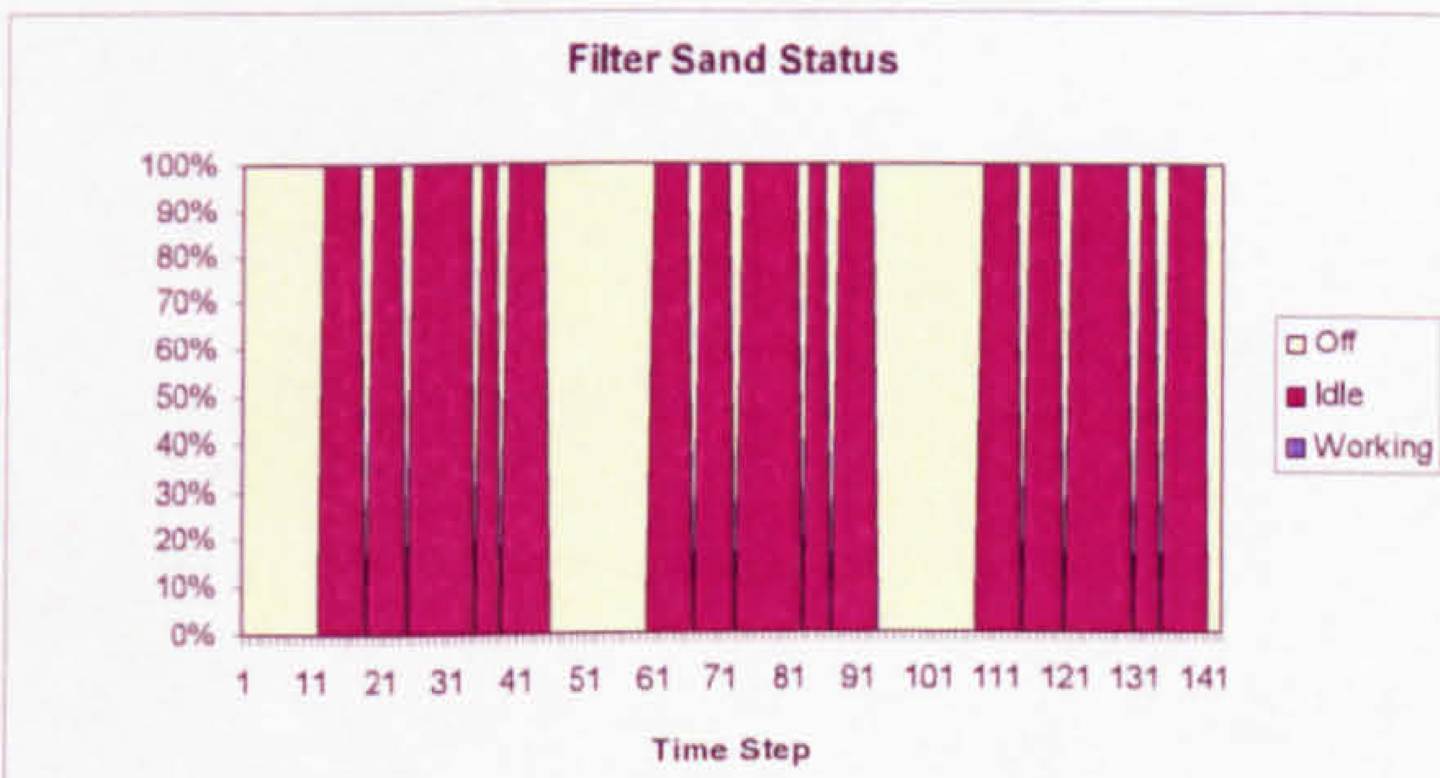


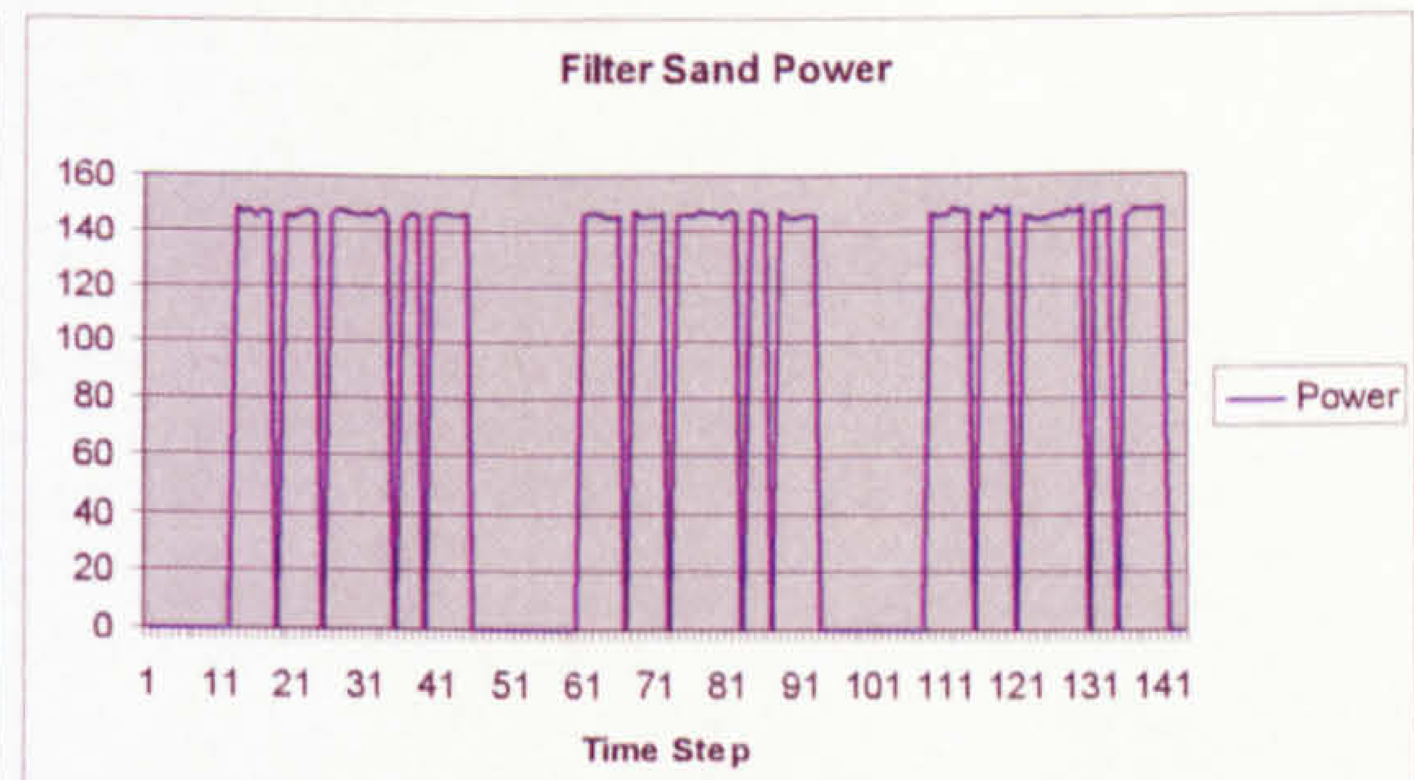


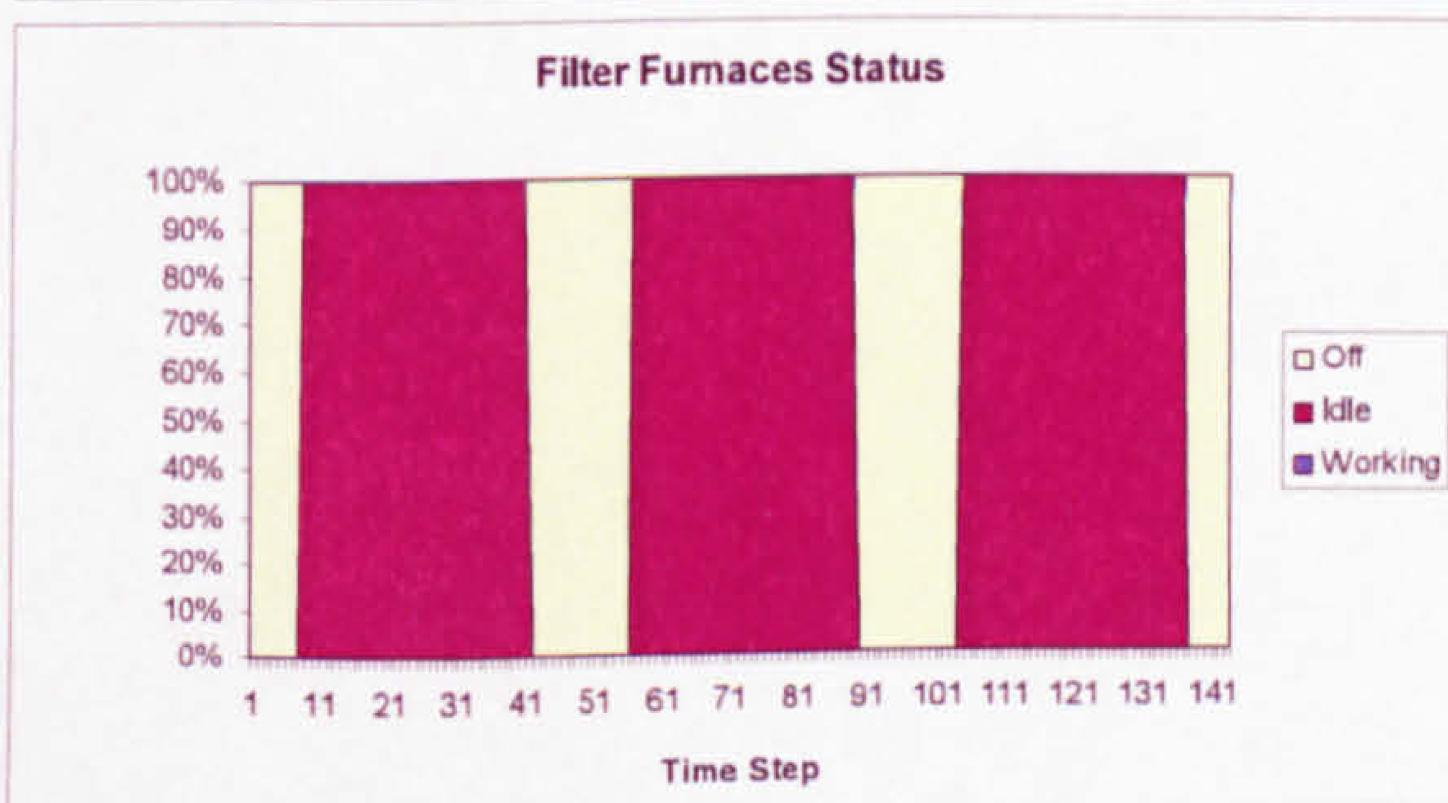


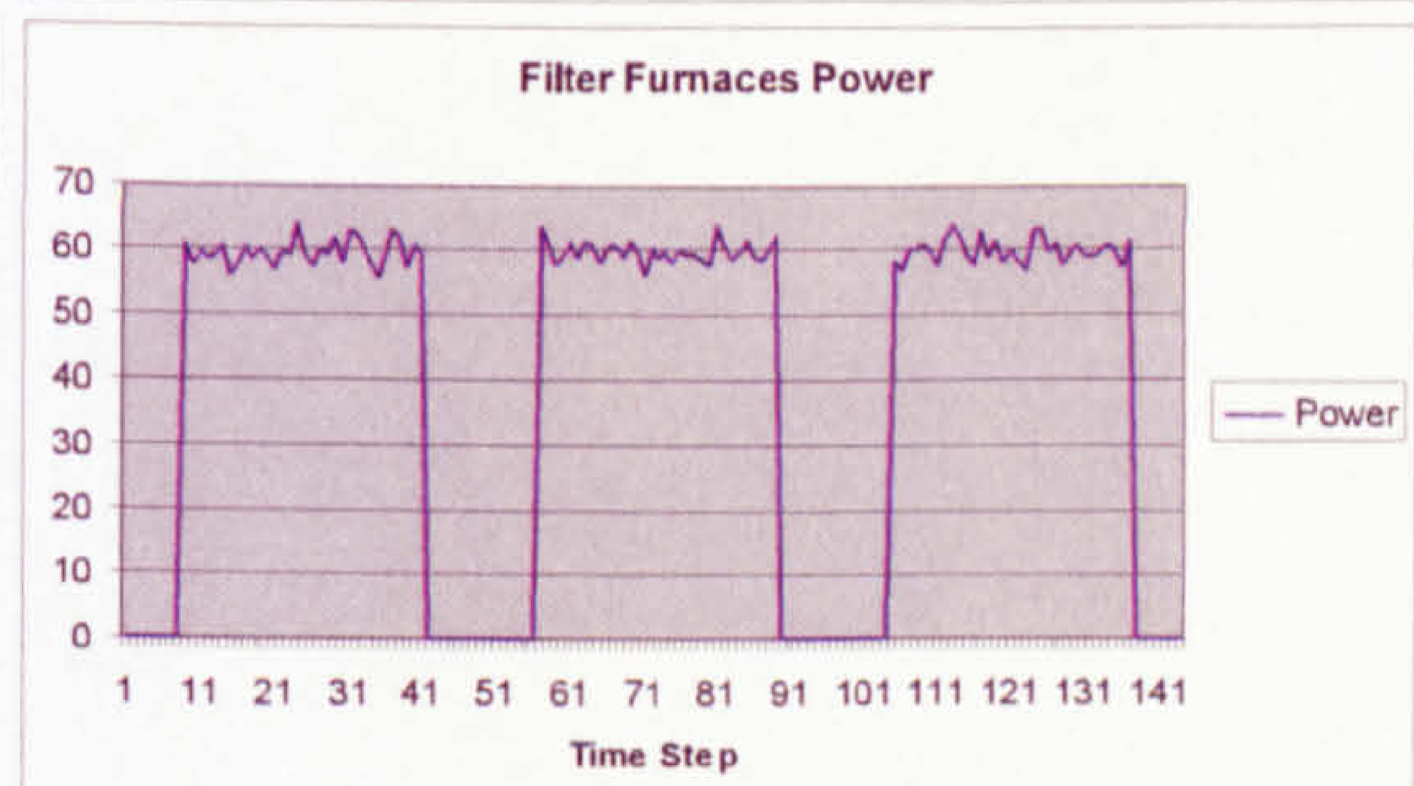

Shot blasting Status
Off
Idle
Working
Time Step

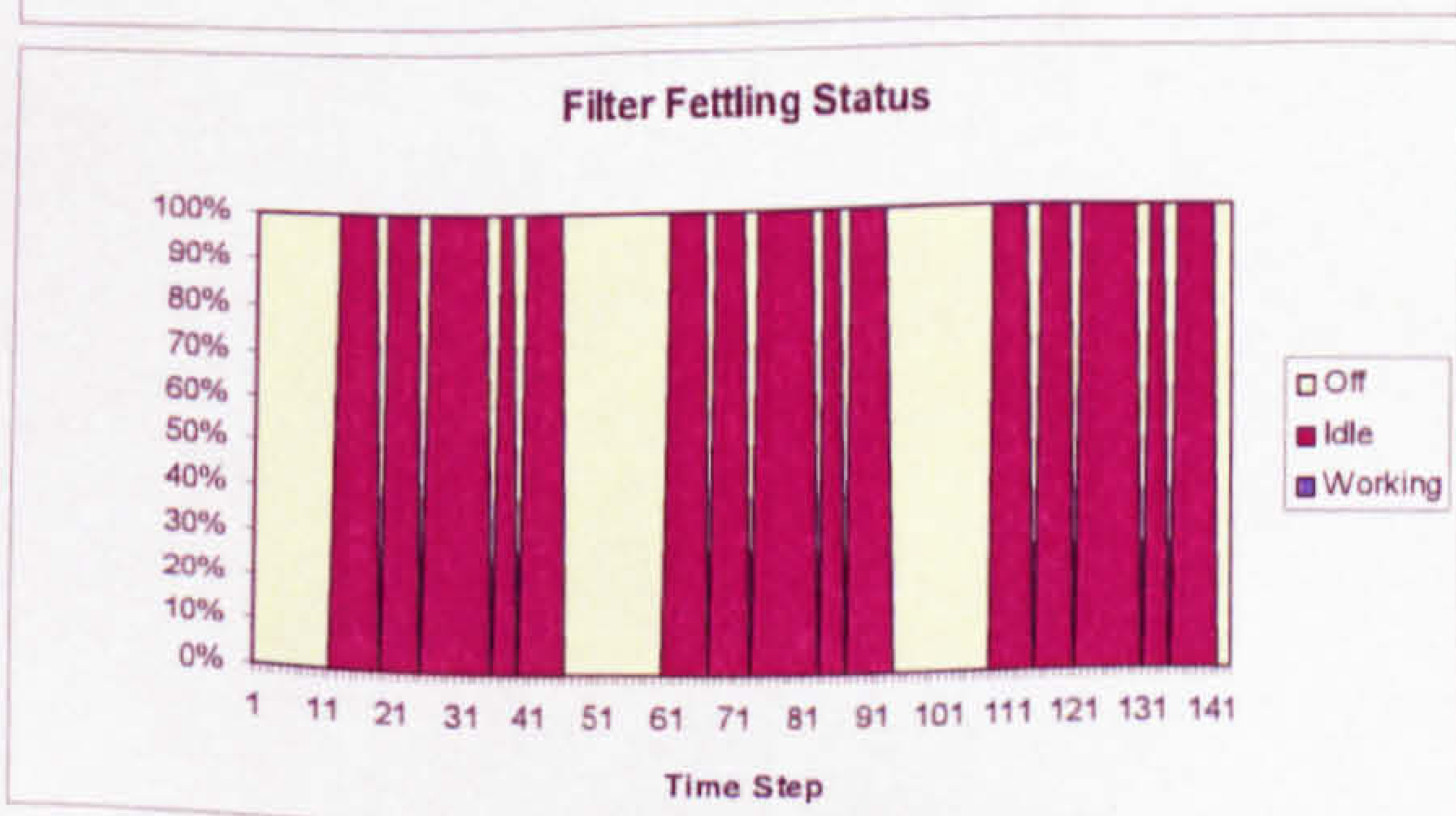

Shot blasting Power
Power
Time Step

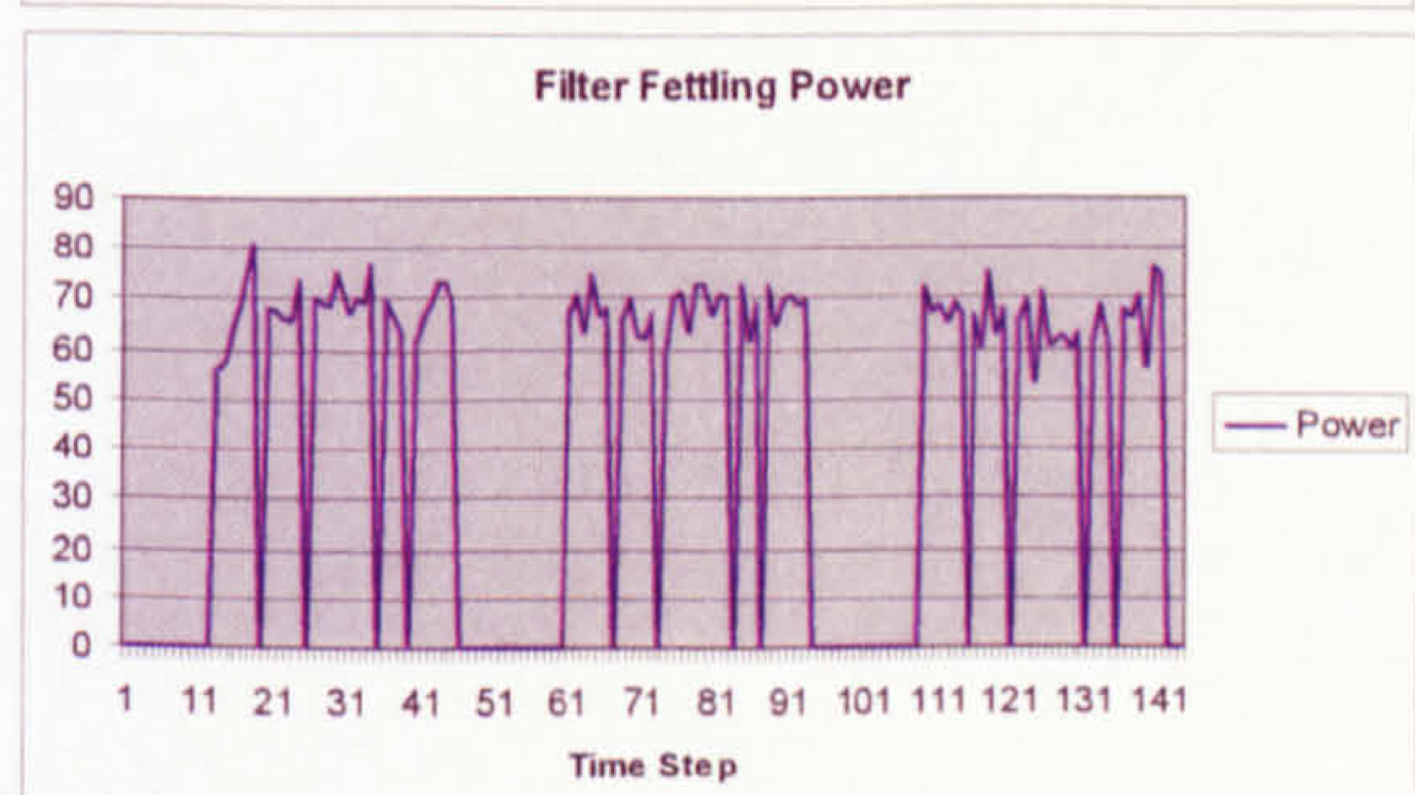

Filter Sand Status
Off
Idle
Working
Time Step


Filter Sand Power
Power
Time Step


Filter Furnaces Status
Off
Idle
Working
Time Step


Filter Furnaces Power
Power
Time Step


Filter Fettling Status
Off
Idle
Working
Time Step


Filter Fettling Power
Power
Time Step